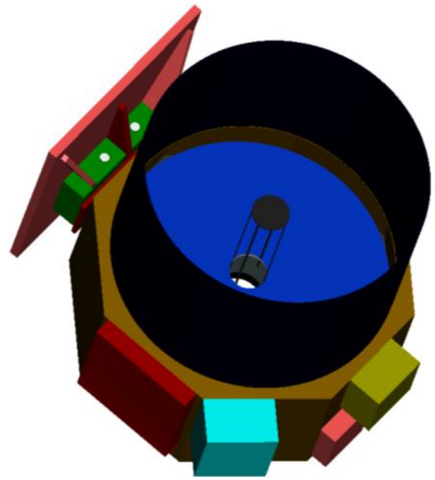
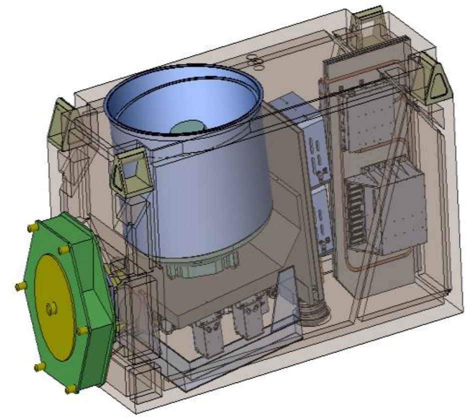
Aerosol-Cloud-Ocean Lidar Mission Concepts and Airborne Science Demonstration

HSRL-1

HSRL-2



ACE HSRL



OPAL HSRL

Chris Hostetler, John Hair, Rich Ferrare, Yongxiang Hu, Mike Behrenfeld, Sharon Burton, Carolyn Butler, Amy Jo Scarino, Detlef Müller, Eduard Chemyakin, and Patricia Sawamura

Outline

- Mission concepts and measurement requirements for next-generation aerosol, cloud, ocean lidars beyond CALIPSO, CATS, and ATLID.
- Implementation concepts: how do they differ from CALIOP on CALIPSO?
- Results from airborne prototypes: are the airborne prototypes showing that we can make the required measurements?

Next-generation mission concepts and measurement requirements for aerosol, cloud, and ocean lidar

Two future mission concepts: ACE and OPAL

- Aerosols-Clouds-Ecosystems (ACE) Mission
  - Mission identified by the US "Decadal Survey"
    - *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (National Research Council, 2007)
  - Includes lidar, radar, polarimeter, and ocean color radiometer
  - Science working groups developed white papers on science and measurement requirements for each instrument

- Ocean Profiling and Atmospheric Lidar (OPAL)
  - A mission concept developed at NASA Langley
  - Scaled down version of ACE lidar provides an example of an instrument realizable in the very near term

- Other concepts are under development, but the above are a good starting point for discussion

ACE Lidar Measurement Requirements

- Aerosol
  - Aerosol optical depth in complex scenes that confound passive sensors (beneath tenuous cirrus, holes between broken cloud, …)
  - Vertically resolved aerosol extinction, backscatter and depolarization
  - Vertically resolved aerosol type and amount to assess/improve chemical transport models
  - Vertically resolved optical, macrophysical, and microphysical properties for aerosol direct forcing and indirect effects
- Cloud
  - Cloud top height
  - Tenuous cloud vertical structure and optical depth
  - Cloud phase and ice water content
- Ocean Ecosystems
  - Aerosol correction for Ocean Color Radiometer
  - Aerosol measurements for ocean-atmosphere interactions
  - Goal: subsurface particulate backscatter for estimates of particulate organic carbon and net primary productivity

Requirements driving instrument architecture

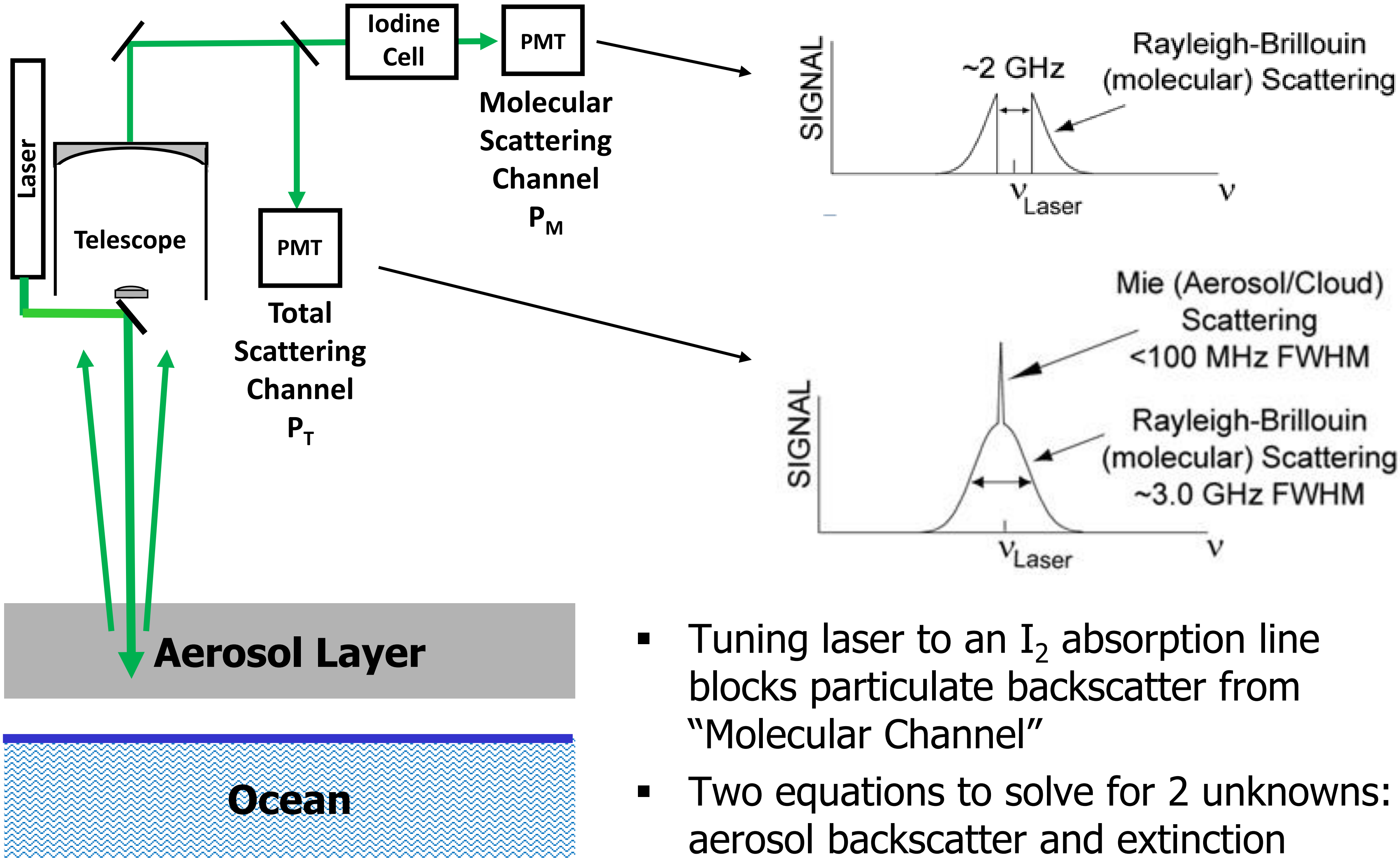
- Aerosol measurements explicitly drove the lidar architecture
  - Driving requirements are for vertically-resolved aerosol microphysics:
    - Aerosol size (DARF and CAI)
    - Index of refraction (DARF and CAI)
    - Single scatter albedo/absorption (DARF)
    - Concentration (CAI)
  - Requires a $3\beta+2\alpha+2\delta$ High Spectral Resolution Lidar (HSRL)
    - Aerosol backscatter at 3 wavelengths: 355, 532, 1064 nm (3β)
    - Aerosol extinction at 2 wavelengths: 355 and 532 nm (2α)
    - Aerosol depolarization at 2 wavelengths: (2δ)
  - Simpler lidar deployed with a polarimeter may be able to meet requirements, but this has yet to be verified.

DARF = Direct Radiative Forcing
CAI = Cloud Aerosol Interactions

- Cloud measurements require HSRL capability at 532 nm only but impact dynamic range of detectors & detection electronics

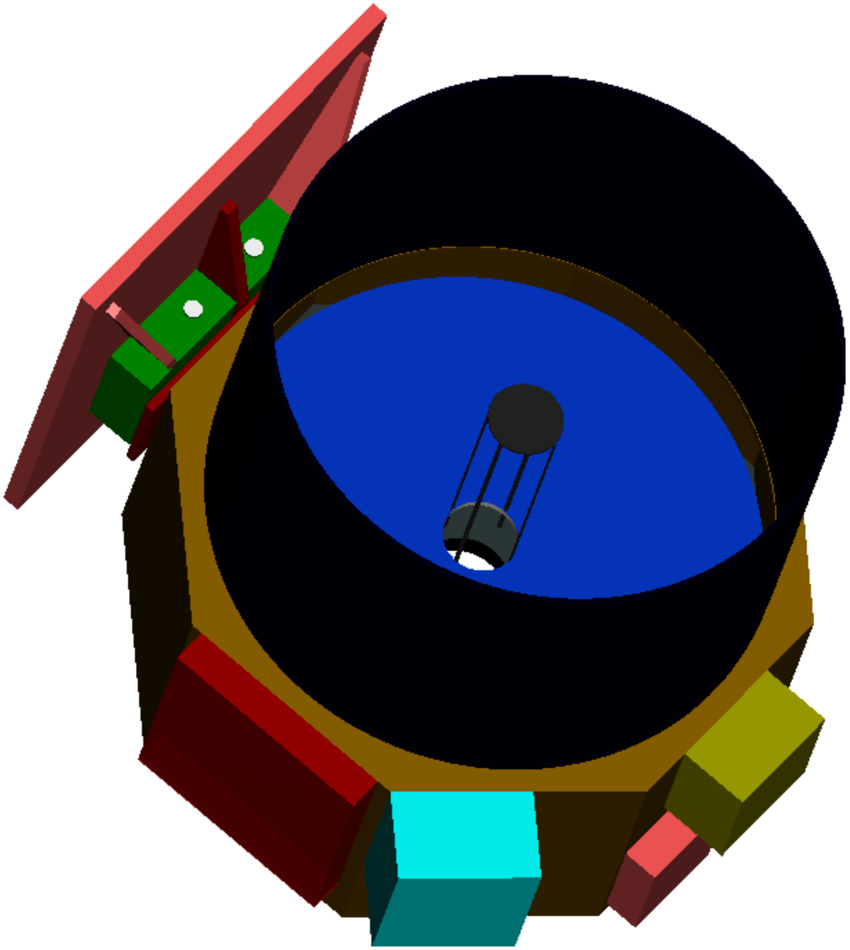
- Ocean subsurface measurements require 532 nm HSRL channel and drive detector speed and dynamic range.

HSRL technique for aerosol profiling



- Tuning laser to an I_2 absorption line blocks particulate backscatter from "Molecular Channel"
- Two equations to solve for 2 unknowns: aerosol backscatter and extinction

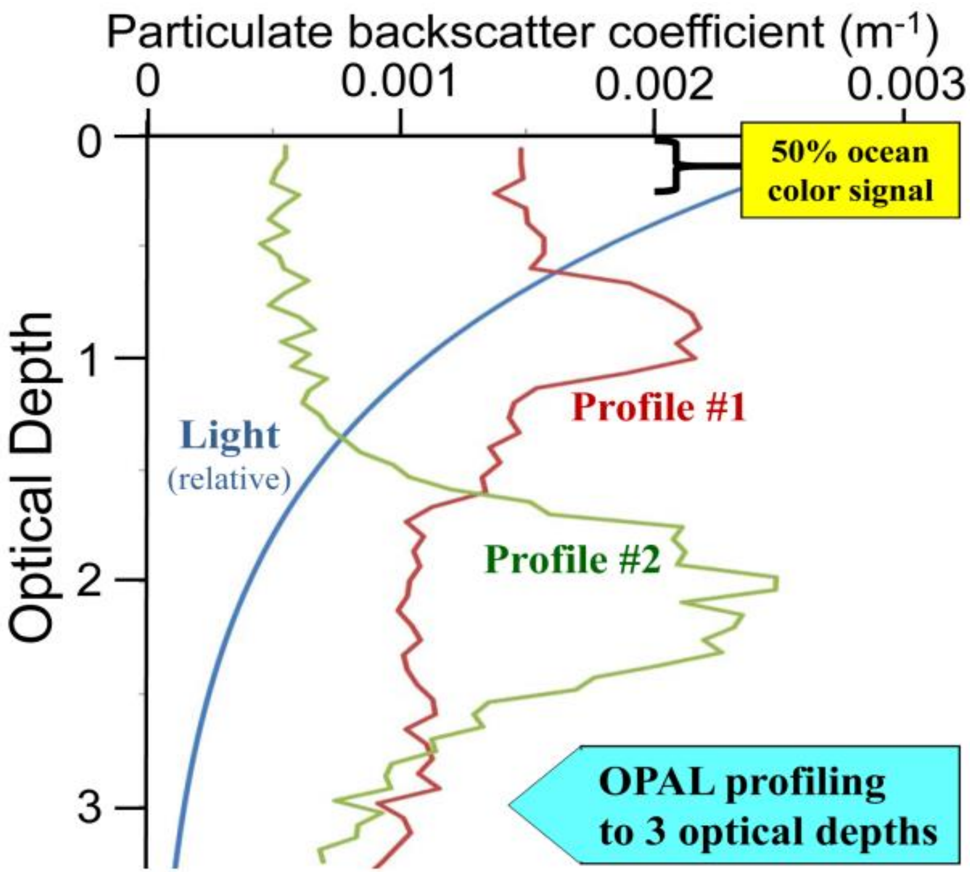
ACE *3β+2α+2δ* High Spectral Resolution Lidar (HSRL) Instrument Concept

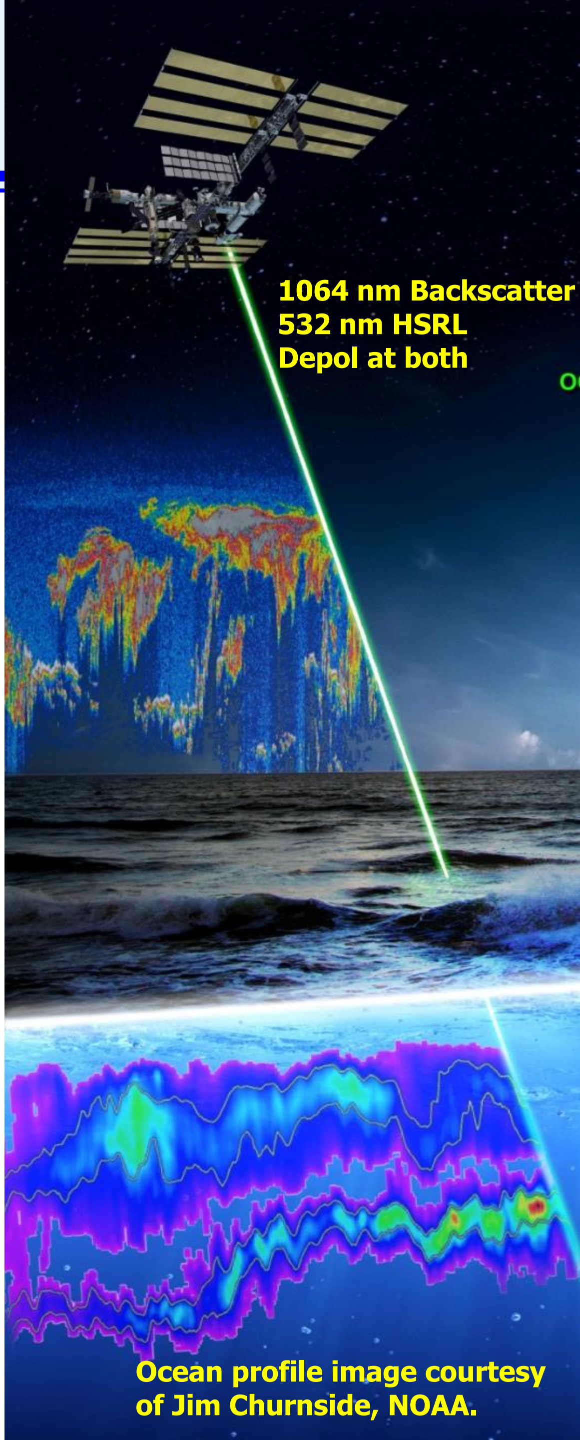


- Measurements
  - Backscatter at 355, 532, 1064 nm **(3β)**
  - Extinction 355 and 532 nm **(2α)**
  - Depolarization at 2 wavelengths **(2δ)**
  - Ocean surface/subsurface at 532 nm (backscatter and Brillouin scatter)
- Products
  - Lidar-only retrieval of aerosol/cloud vertical distribution, aerosol optical and microphysical properties, and cloud optical and microphysical properties
  - Lidar-only retrievals of ocean subsurface particulate backscatter
  - Lidar + polarimeter retrievals of aerosol optical and microphysical parameters
  - Lidar + radar cloud retrievals

One of many possible realizations:
Transmitter: 25 W average power
Telescope: 1.5-m diameter

OPAL: ocean profiling at 532 nm and atmospheric profiling at 532 and 1064 nm



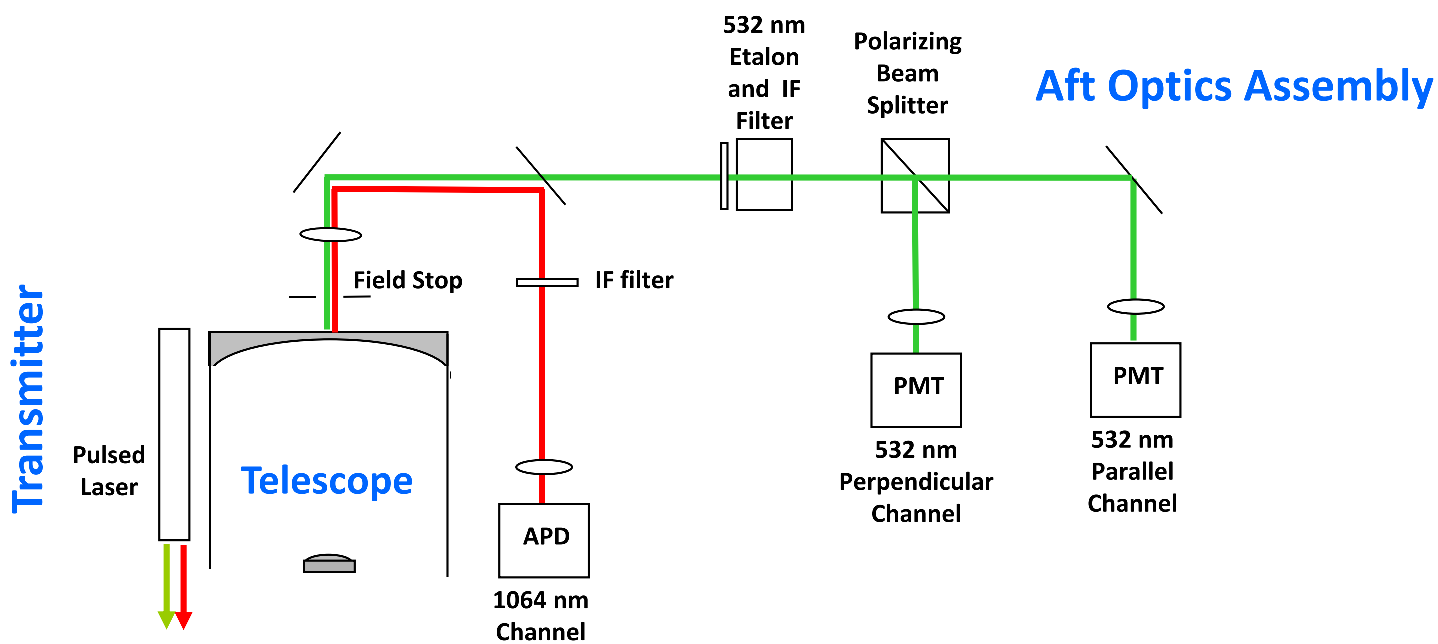


- Objective: measure vertical structure of phytoplankton to reduce uncertainties in NPP
- OPAL measurements will penetrate 70% of the euphotic zone (i.e., depth range where light levels are sufficient for photosynthesis).

How are the ACE and OPAL lidar concepts different from CALIPSO?

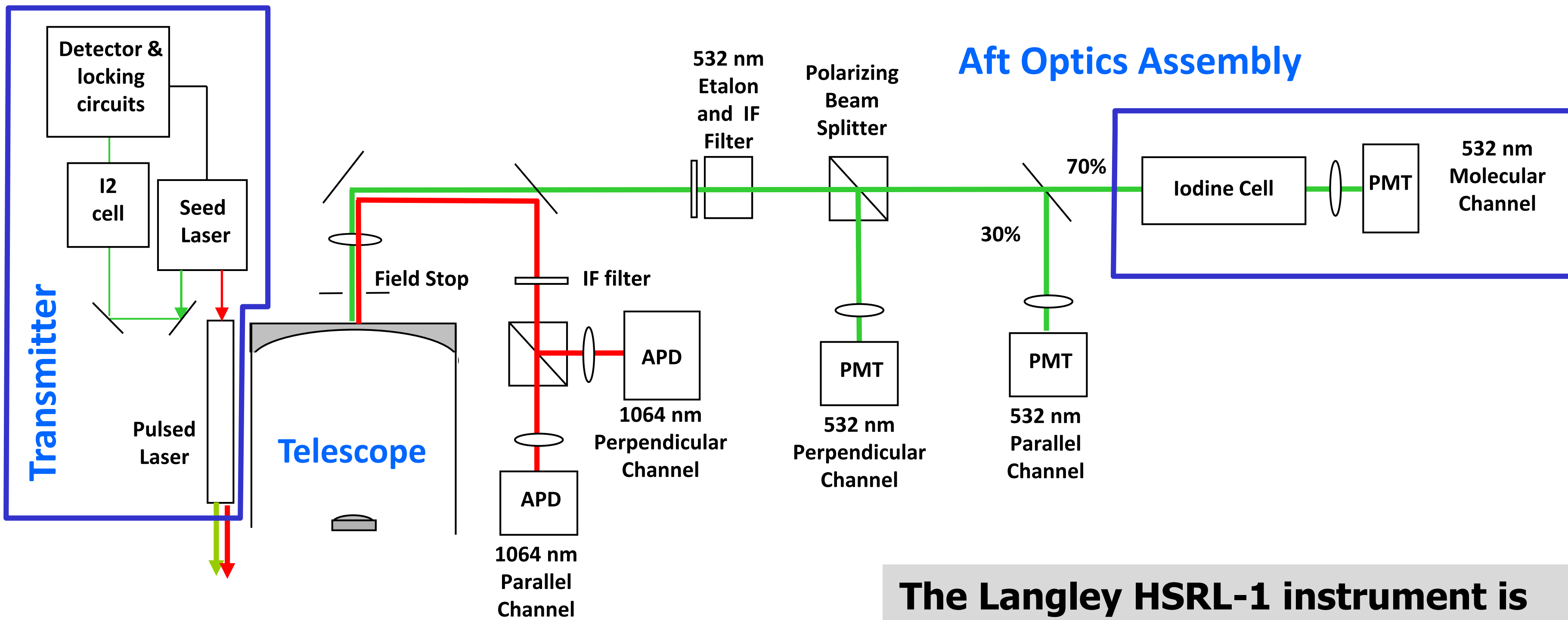
CALIOP on CALIPSO: *2β+1δ*

- Robust design
- 8 years on-orbit operations!



OPAL Concept:
A *2β+1α+2δ* High Spectral Resolution Lidar (HSRL)

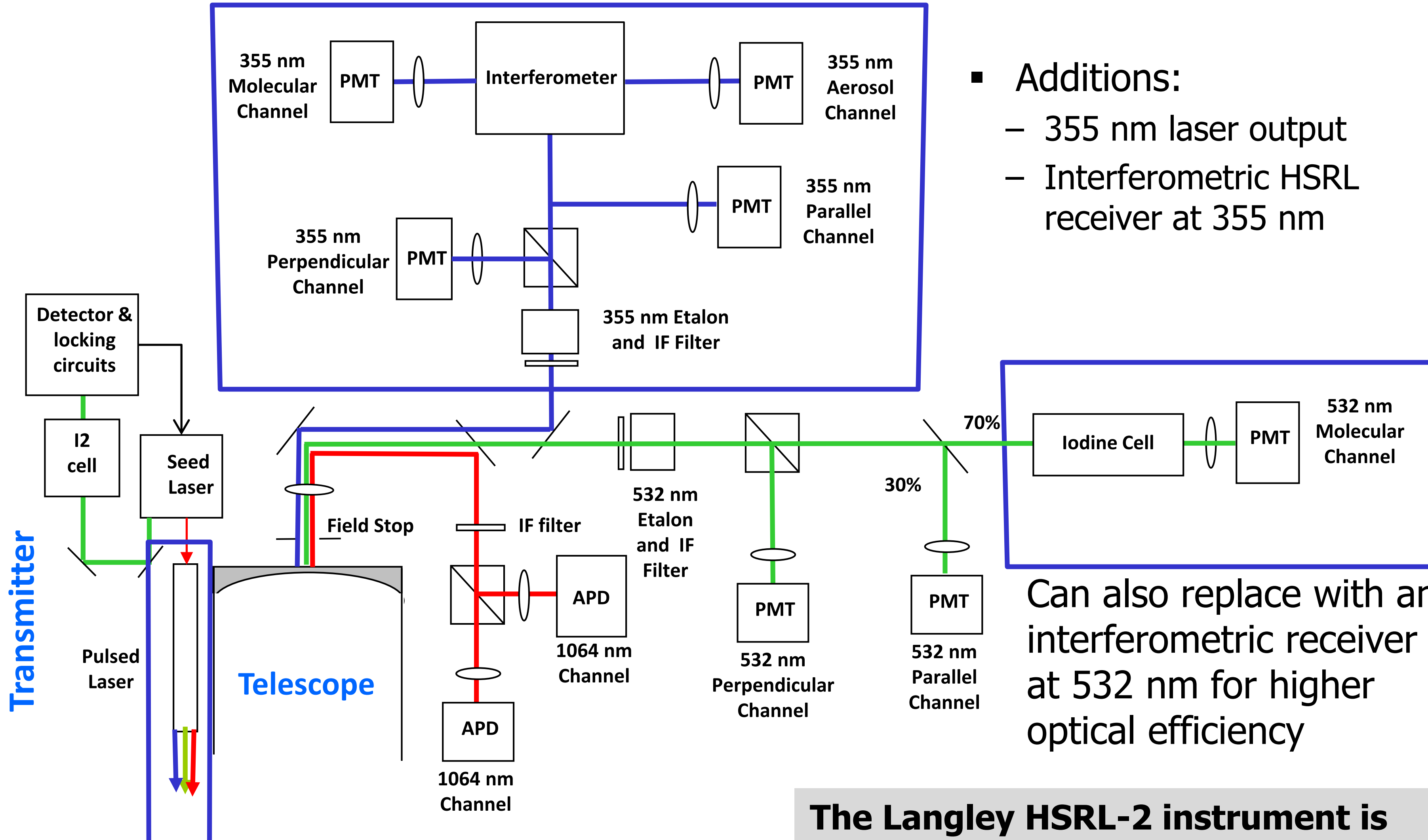
- Additions:
  - Single-frequency laser with seed laser and frequency locking
  - Iodine cell and extra detector in receiver



The Langley HSRL-1 instrument is the airborne prototype for OPAL:
> 25 deployments
>350 flights

ACE Concept: a $3\beta+2\alpha+3\delta$ HSRL

- Additions:
  - 355 nm laser output
  - Interferometric HSRL receiver at 355 nm



Can also replace with an interferometric receiver at 532 nm for higher optical efficiency

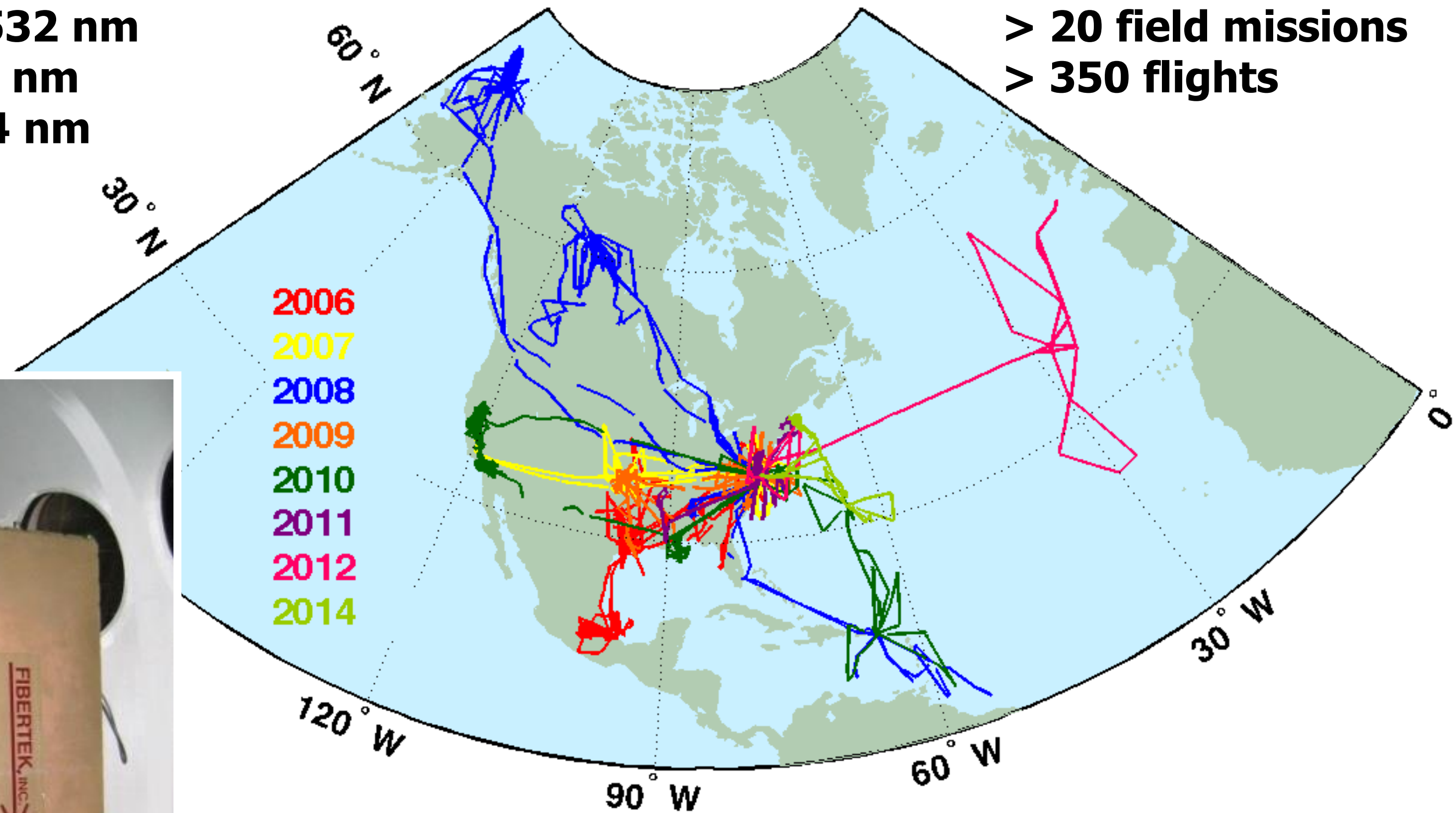
The Langley HSRL-2 instrument is the airborne prototype for ACE:
4 deployments
> 50 flights

Are airborne prototypes showing that we can make these measurements?

The NASA Langley HSRL-1 instrument has flown extensively in diverse regions and different seasons

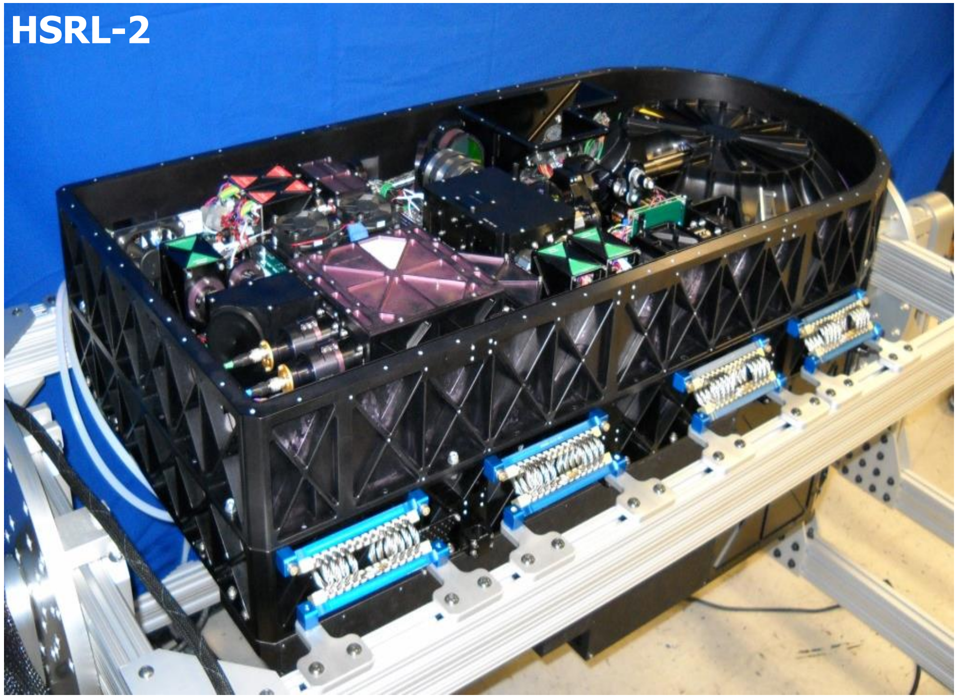
HSRL technique at 532 nm
Backscatter at 1064 nm
Depol at 532 & 1064 nm

> 20 field missions
> 350 flights



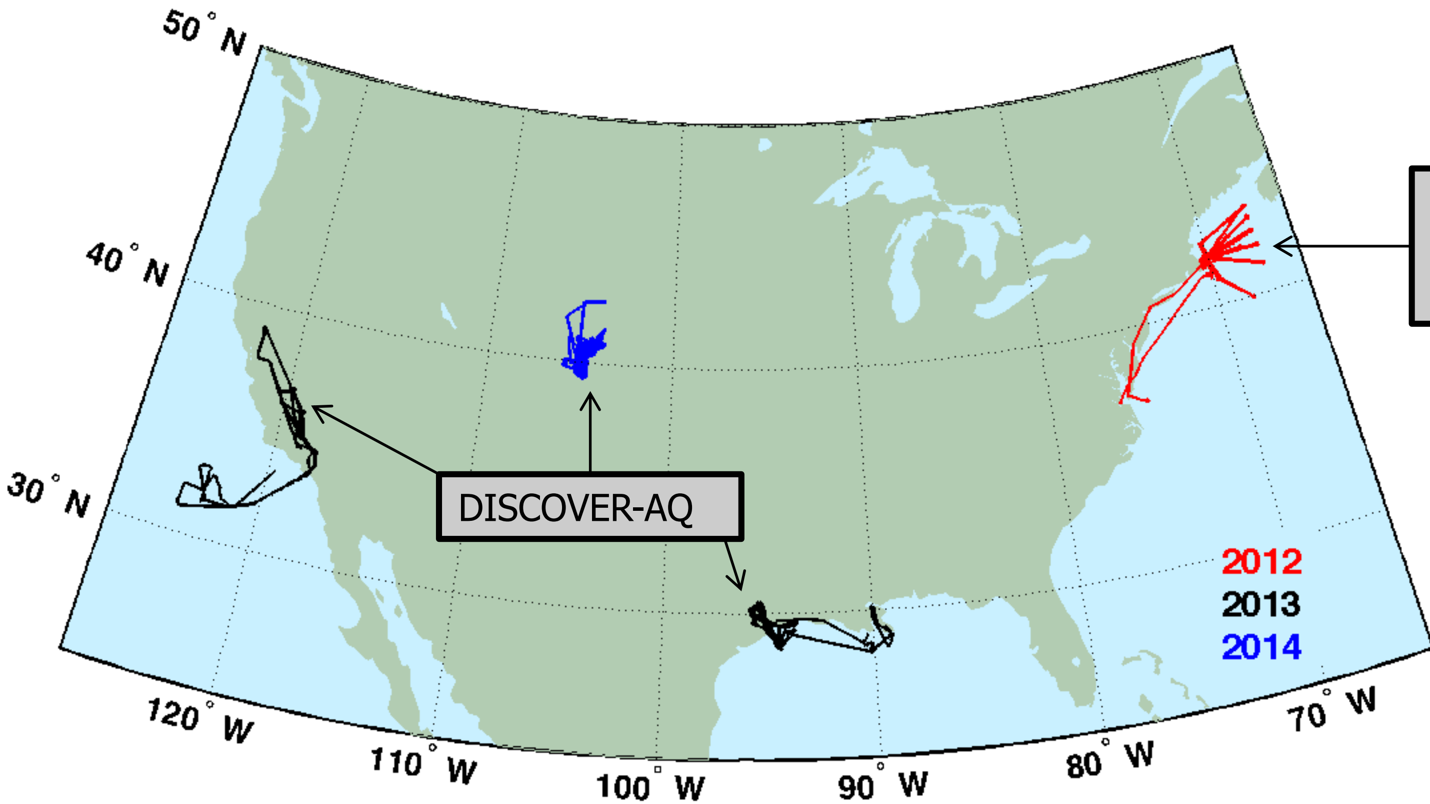
HSRL-1 typically deployed on the Langley King Air aircraft; Azores mission conducted on Wallops P3-B

HSRL-2: the ACE *3β+2α+3δ* Lidar Simulator



- Built for deployment on ER-2 and other aircraft
  - Not flown on ER-2. First flights on ER-2 in 2015
- Meets all ACE atmospheric measurement requirements
- Flown on 4 field missions
- Operational data processing code has been demonstrated on field data

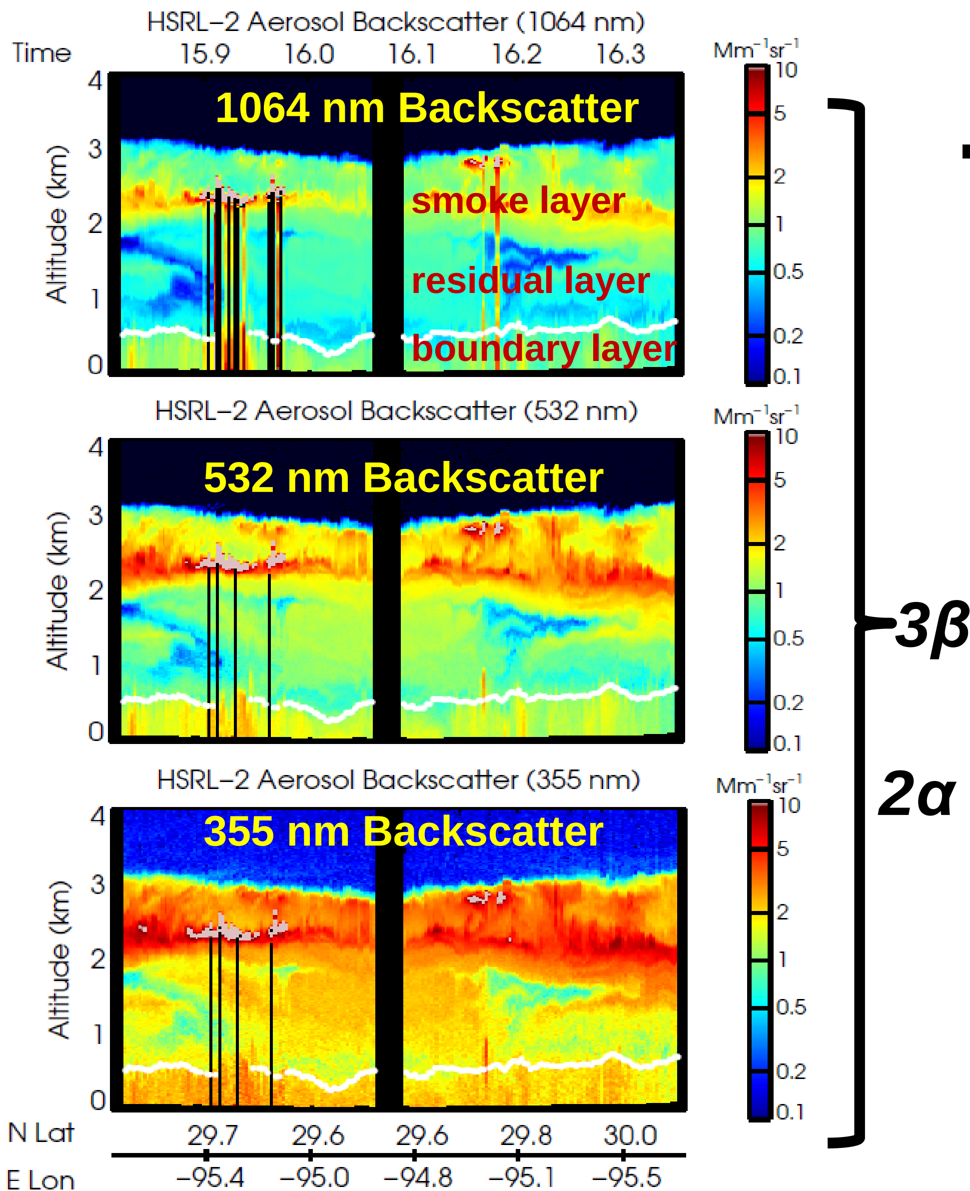
HSRL-2 has been deployed on 4 major field missions



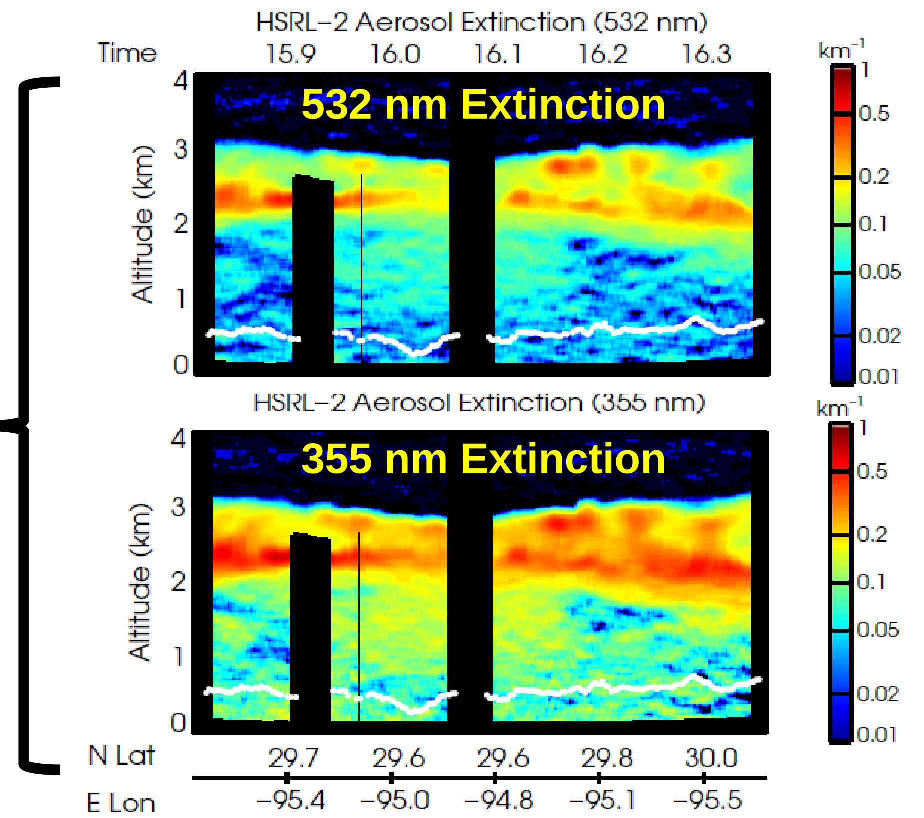
- Missions all involved a second aircraft making in situ aerosol measurements and ground stations with remote sensing and in situ instrumentation
- Extensive corroborative data enables validation of lidar aerosol retrievals (e.g., extinction, microphysical parameters, type)
- Validation comparisons are ongoing

“3β+2α+3δ" HSRL lidar measurement capability identified for ACE DARF, CAI, and ocean-aerosol objectives

09/13/2013 DISCOVER-AQ flight on B200 aircraft

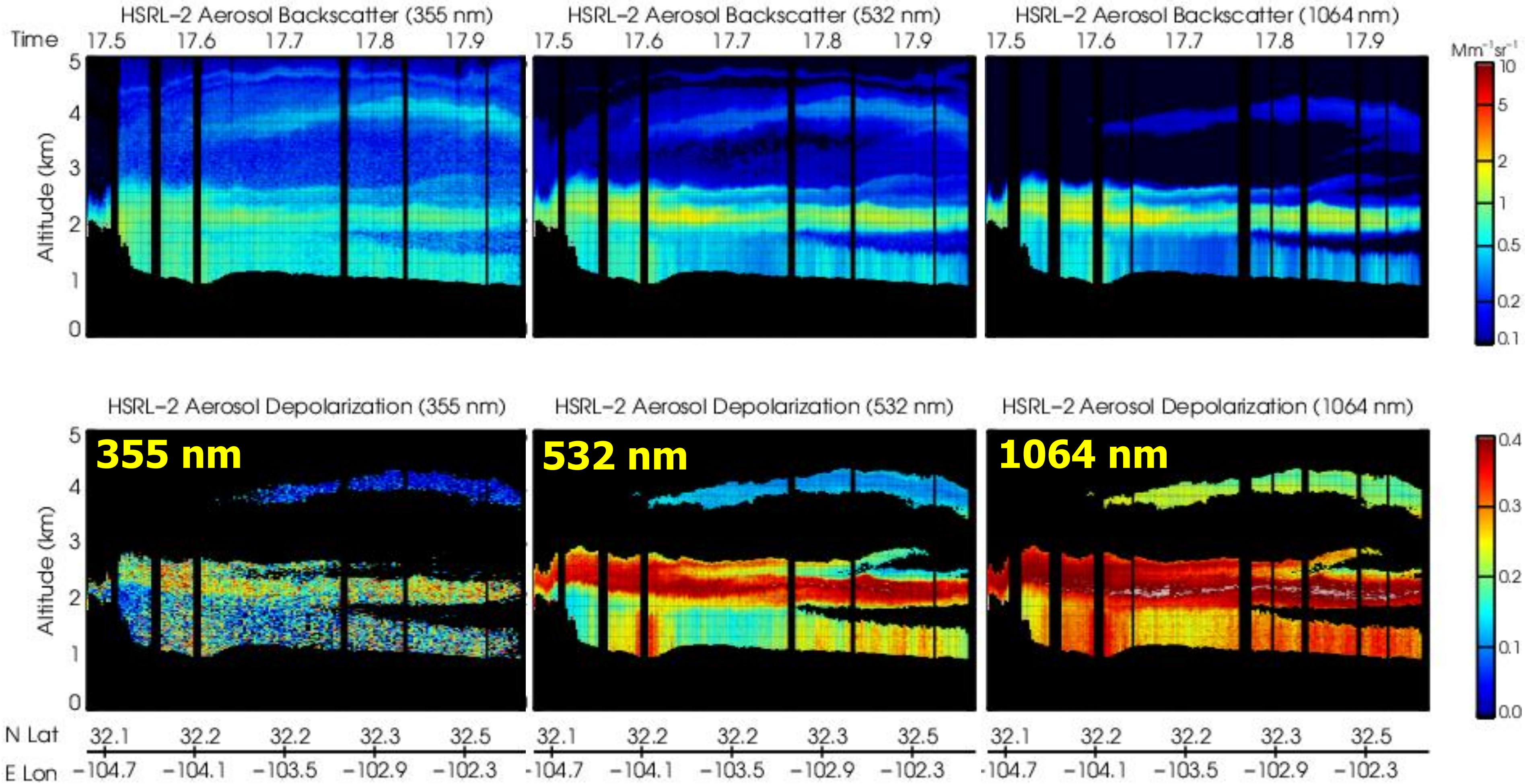


- High Spectral Resolution Lidar (HSRL) provides independent retrievals of aerosol extinction and backscatter
- HSRL-2 Capabilities
  - Backscatter at 355, 532, and 1064 nm
  - Extinction at 355 and 532 nm (HSRL)
  - Depolarization at 355, 532, 1064 nm



Aerosol depolarization example from HSRL-2

Data acquired on return transit from DISCOVER-AQ/PODEX

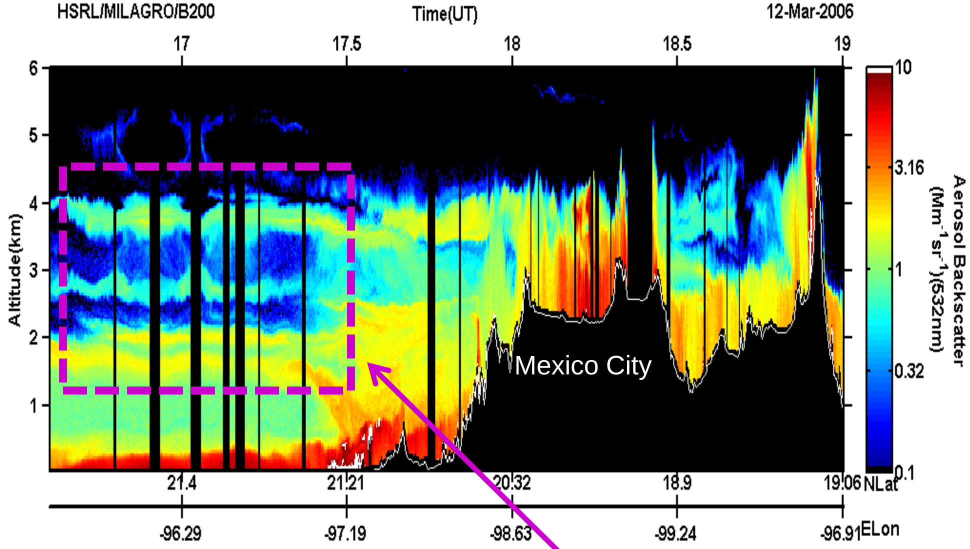


Depolarization required at only 2 wavelengths for ACE.
The choice of those wavelengths is under study.

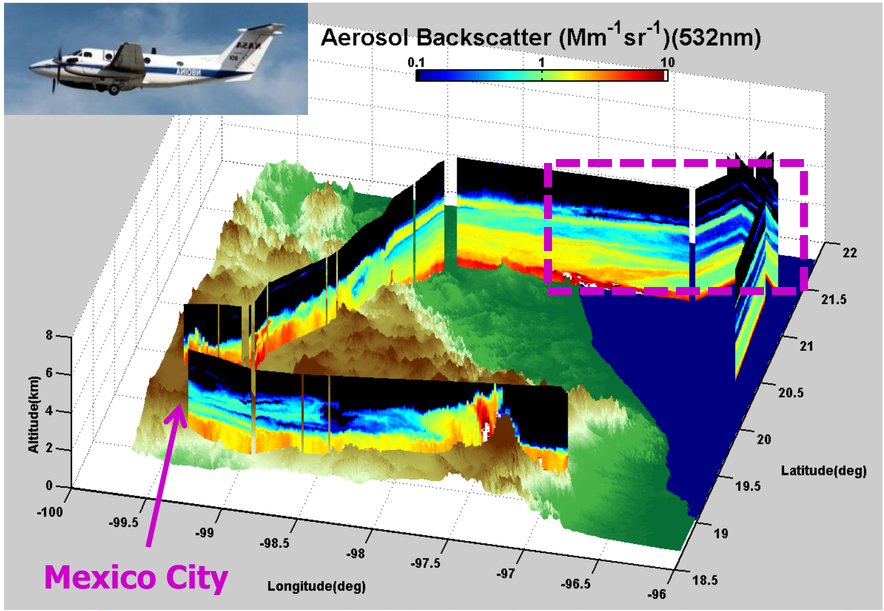
Aerosol Retrievals

Airborne HSRL-1 Measurements Used to Evaluate WRF-Chem Model

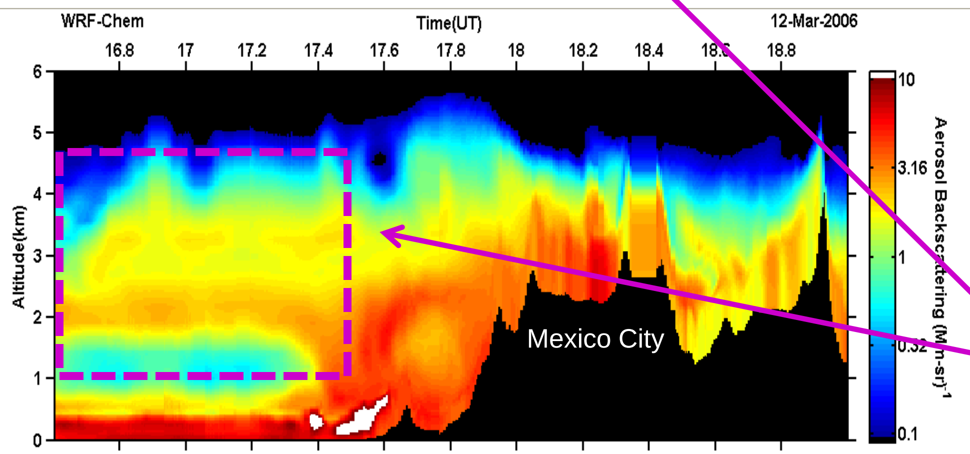
Backscatter measured by airborne HSRL



NASA/LaRC B200/HSRL March 12, 2006



Backscatter predicted by WRF-Chem model

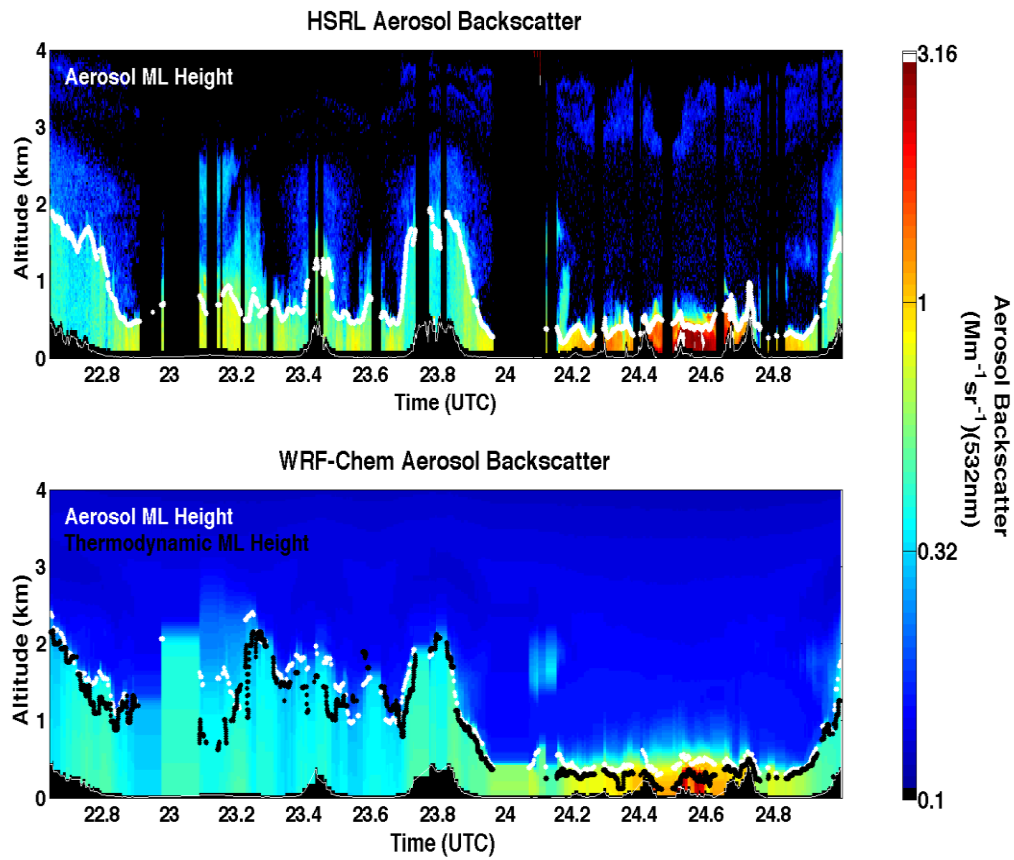


(Fast et al., 2011, BAMS)

- Airborne HSRL data:
  - reveal complexity of mixing and transport of particulates
  - used to indirectly evaluate meteorological predictions
- Model can reproduce most aspects of PBL in vicinity of Mexico City
- Model requires smaller vertical grid spacing to resolve shallow layering observed by lidar

Mixed Layer Heights

- Mixed Layer (ML) heights derived from daytime-only cloud-screened aerosol backscatter profiles measured by HSRL
- Automated technique uses a Haar wavelet covariance transform with multiple wavelet dilations to identify sharp gradients in aerosol backscatter at the top of the ML (adapted from Brooks, JAOT, 2003)
- HSRL ML heights combine results from automated algorithm and manual inspection of HSRL backscatter profiles
- ML heights computed for 15 science campaigns (212 flights) since 2006
- HSRL ML heights have been used to validate models, e.g. WRF-Chem

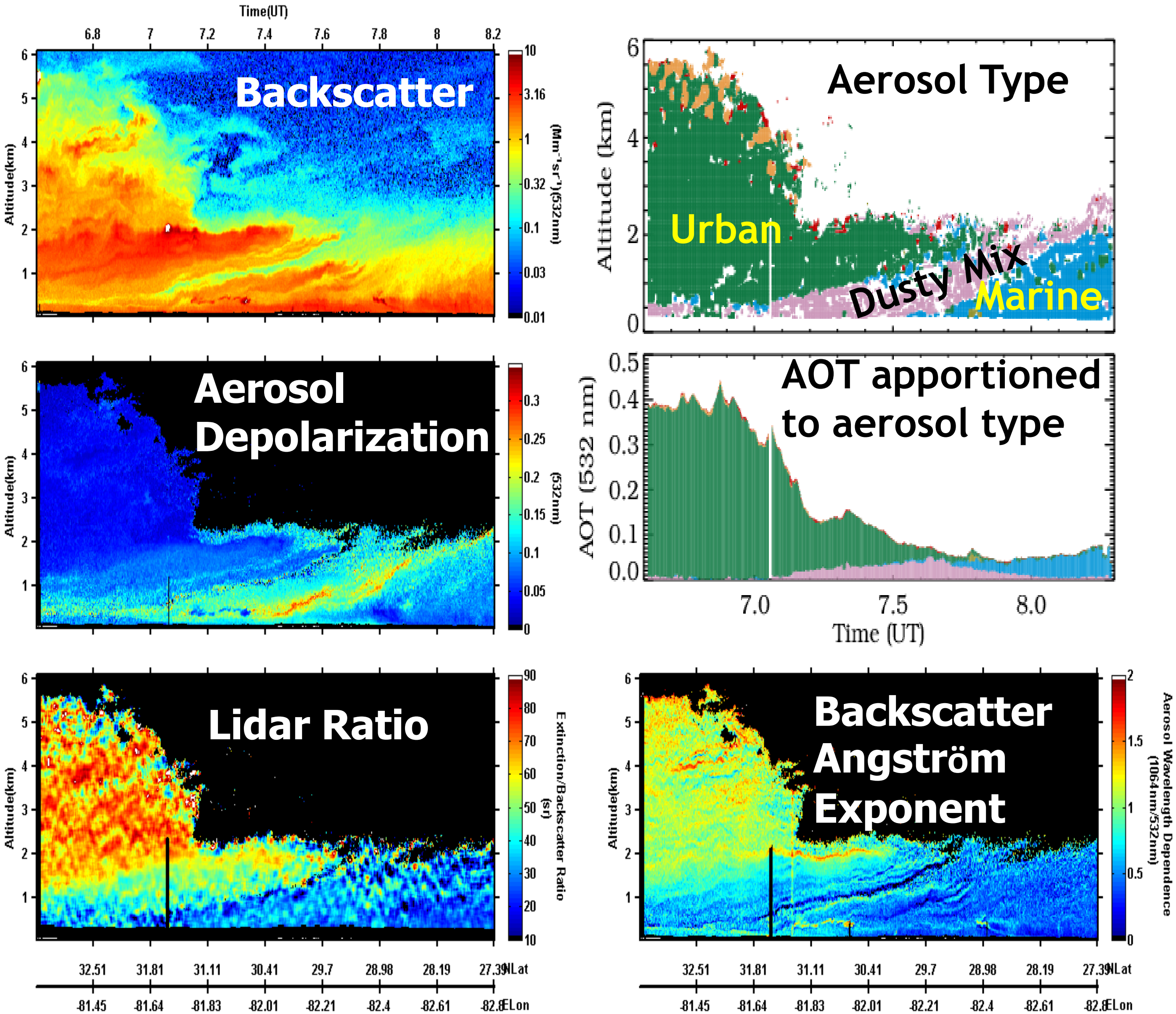


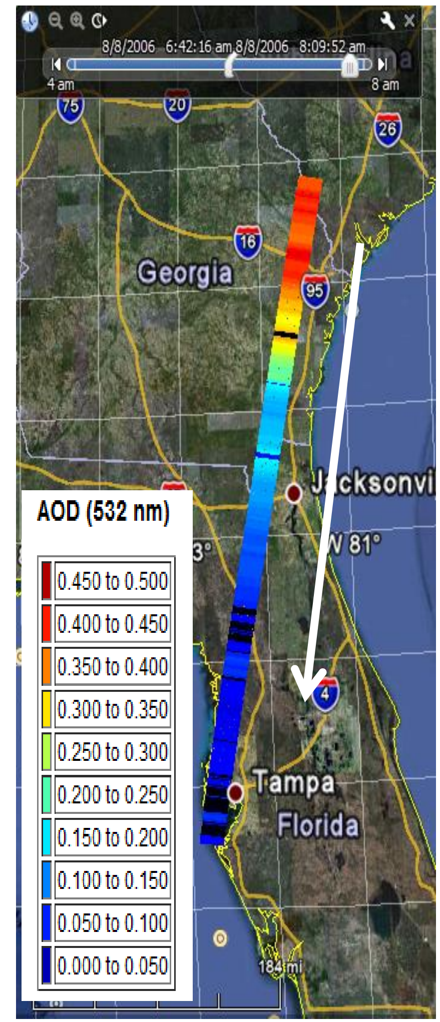
Comparison of mixed layer heights from airborne HSRL, ground-based measurements, and the WRF-Chem model during CalNex and CARES, Scarino et al. *Atmos. Chem. & Phys.*, 2014

Aerosol Typing and Mixing Analyses

- HSRL lidars provide accurate "intensive" observables from which aerosol type can be inferred
  - Intensive observable: depends only on aerosol type and NOT on amount
    - Extinction-to-backscatter ratio
    - Backscatter color ratio at two pairs of wavelengths
    - Depolarization ratio
    - Spectral depolarization ratio (ratio of depolarization at 2 wavelengths)
    - Extinction angstrom exponent (355 and 532 nm)
- Aerosol typing using HSRL-1 data ($2\beta + 1\alpha + 2\delta$, 532 and 1064 nm):
  - Identifying aerosol type and partitioning AOD by type.
  - Results useful for assessing/improving chemical transport models
- Recently, analysis extended to quantifying mixing ratio of aerosol types

HSRL capability plus polarization sensitivity enable aerosol typing and partitioning aerosol optical depth by type



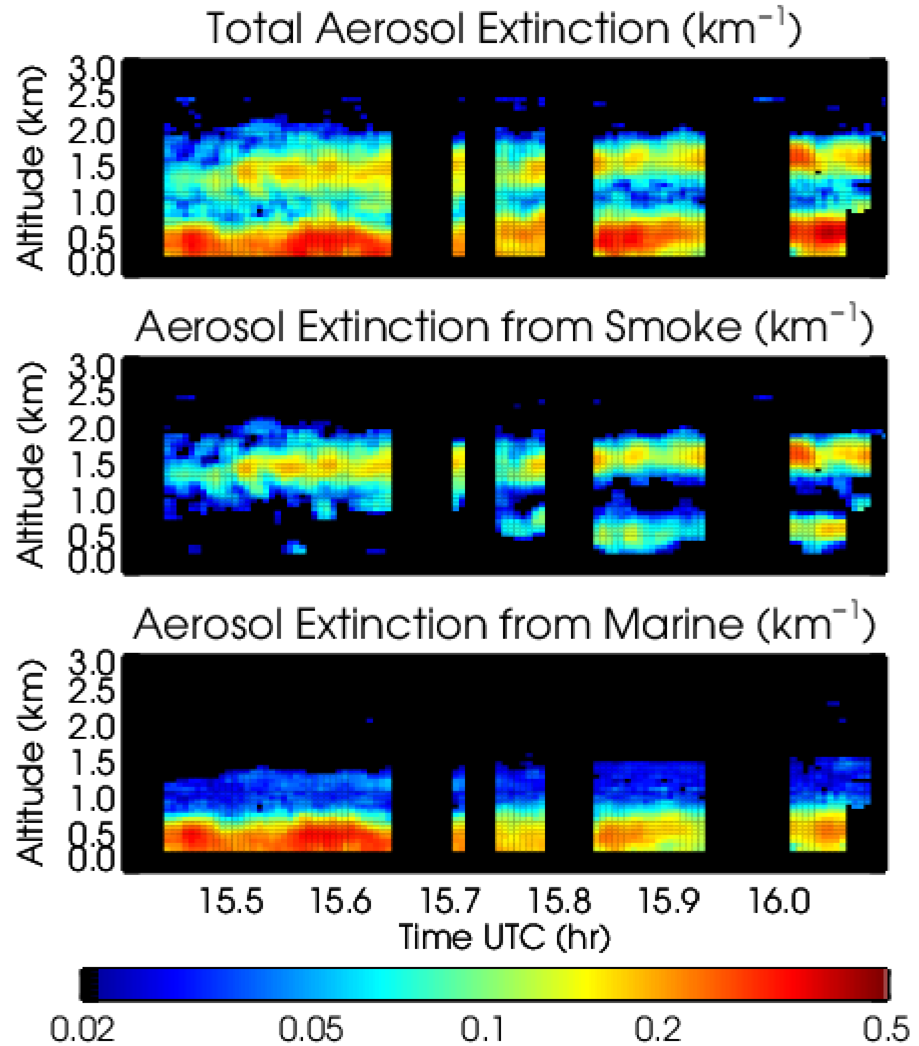


Burton et al., 2012, Atmos. Meas. Tech.

Aerosol mixing: quantifying separate contributions from pure aerosol types

- Heritage typing scheme identifies 7 types which include mixtures of pure aerosol types: dust, dusty mixture, marine, polluted marine, urban, smoke, and fresh smoke.
- New analysis computes mixing ratios of pure types in the same volume.
- Models often agree with satellite on optical depth but disagree on aerosol type. New scheme provides significant advance in quantitative evaluation and improvement of transport models.

Separating mixtures of aerosol types using airborne HSRL, Burton et al. *Atmos Meas Tech*, 2014



Lofted transported smoke layer mixing with marine boundary layer, Gulf of Mexico, March 28, 2006; data acquired by LaRC airborne HSRL

Aerosol Microphysical Retrievals

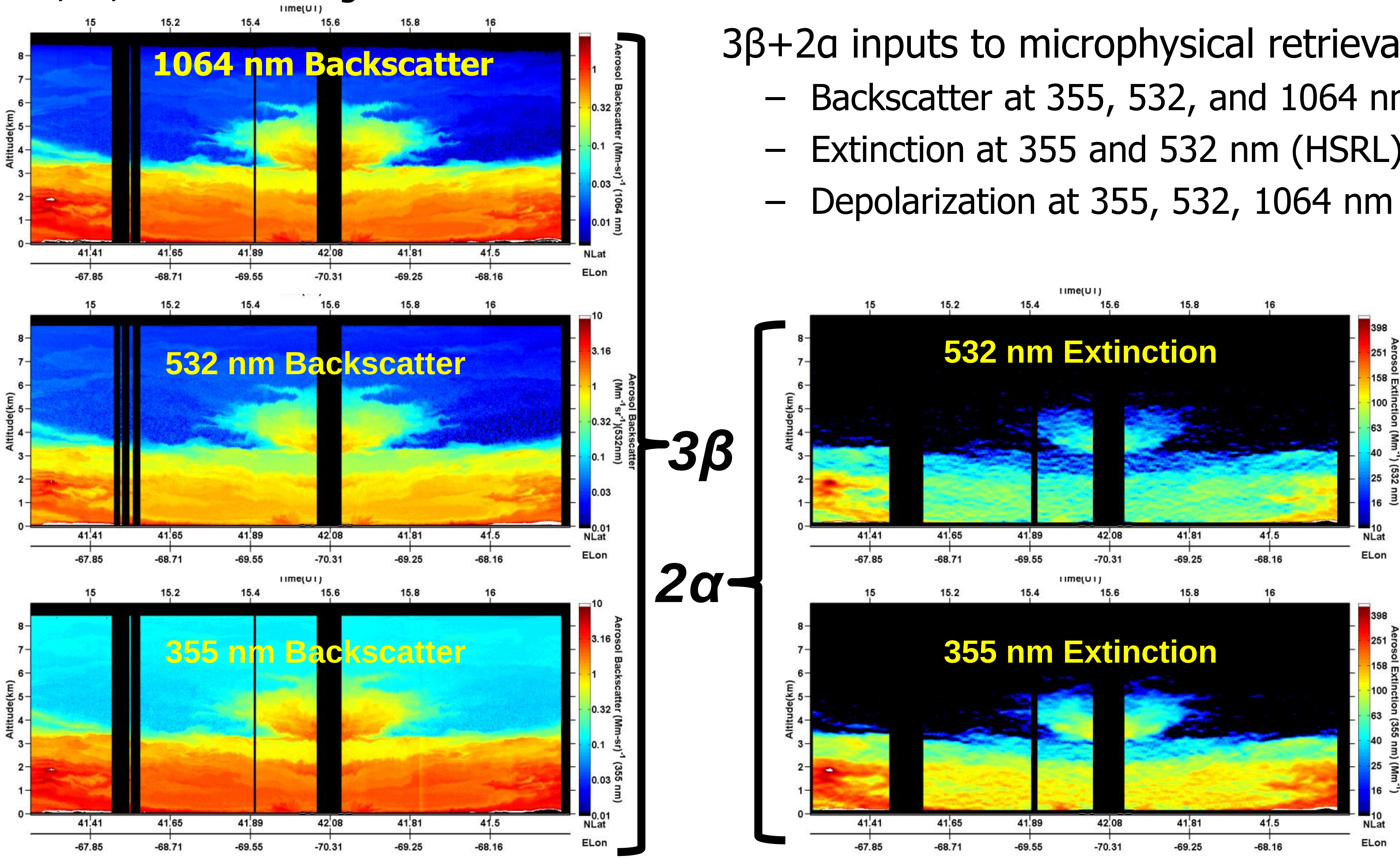
- Vertically resolved retrievals of
  - Effective radius
  - Real and imaginary index of refraction
  - Single scatter albedo
  - Concentration
- Microphysical parameters provide
  - Alternate proxy for aerosol composition (vs type)
  - Separation of scattering and absorption
  - Potential proxy for CCN
- Requires the *3β+2α* retrieval technique originally developed by Detlef Müller but implemented now by several groups including some EARLINET sites.

Airborne multi-wavelength "3β+2α" HSRL measurements from the TCAP field campaign

07/17/2012 TCAP flight on B200 aircraft

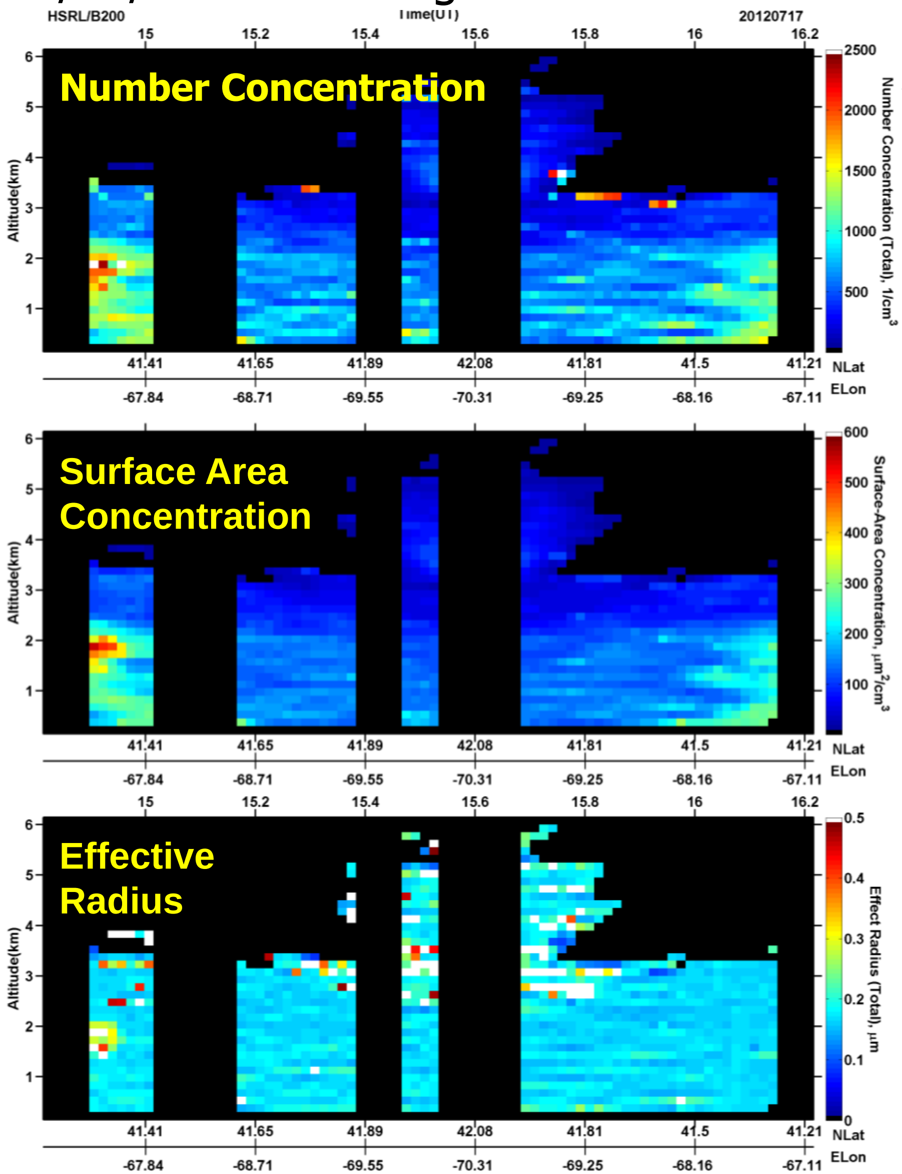
3β+2α inputs to microphysical retrievals

- Backscatter at 355, 532, and 1064 nm
- Extinction at 355 and 532 nm (HSRL)
- Depolarization at 355, 532, 1064 nm



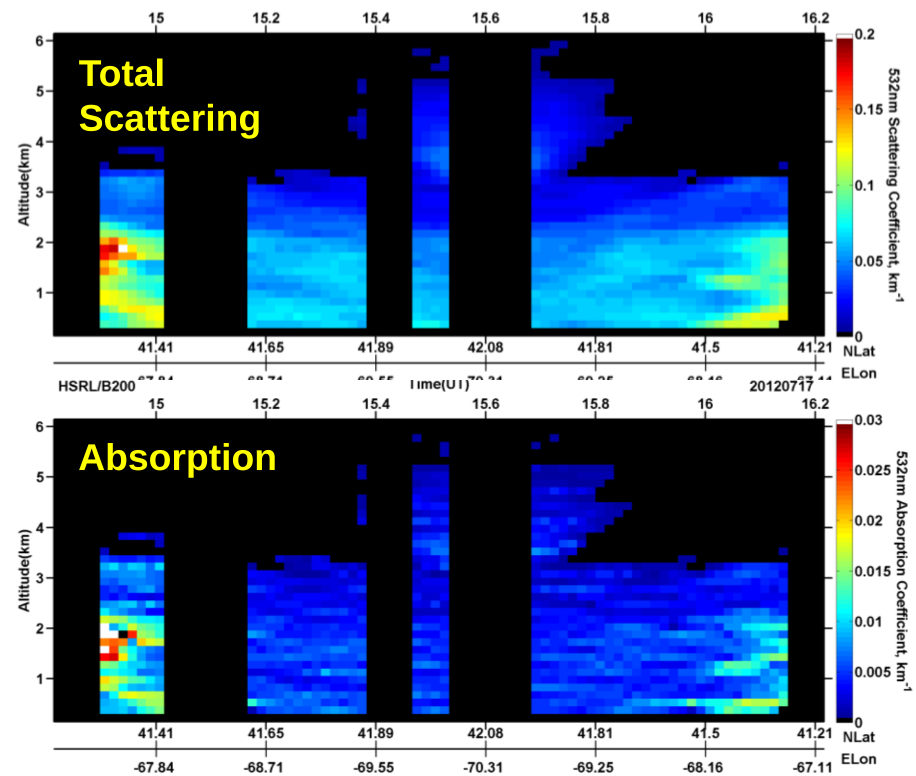
“3β+2α" microphysical retrievals from TCAP

07/17/2012 TCAP flight on B200 aircraft

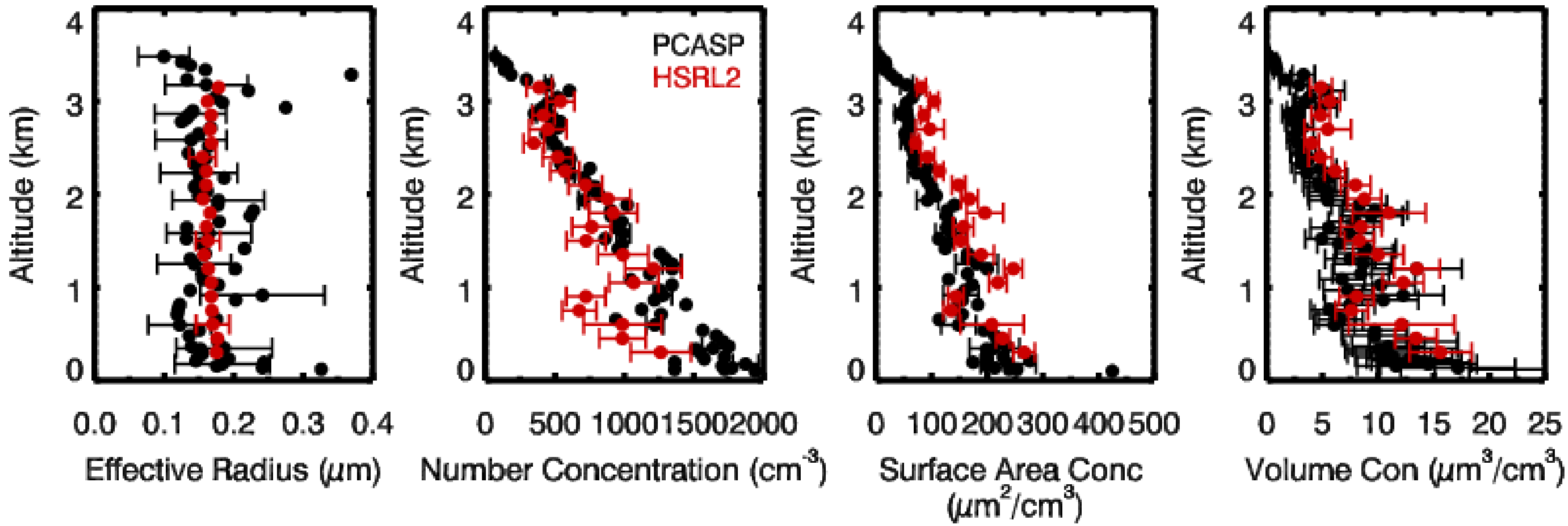


- Inversion with Regularization (Müller et al. 1999, Veselovskii et al 2002)
- Produces horizontally and vertically resolved curtains of microphysics including:

  Effective radius – Complex index of refraction – Scattering coefficient – Absorption coefficient – Single scatter albedo – Number, Surface and Volume Concentration



Microphyscial Retrievals from TCAP

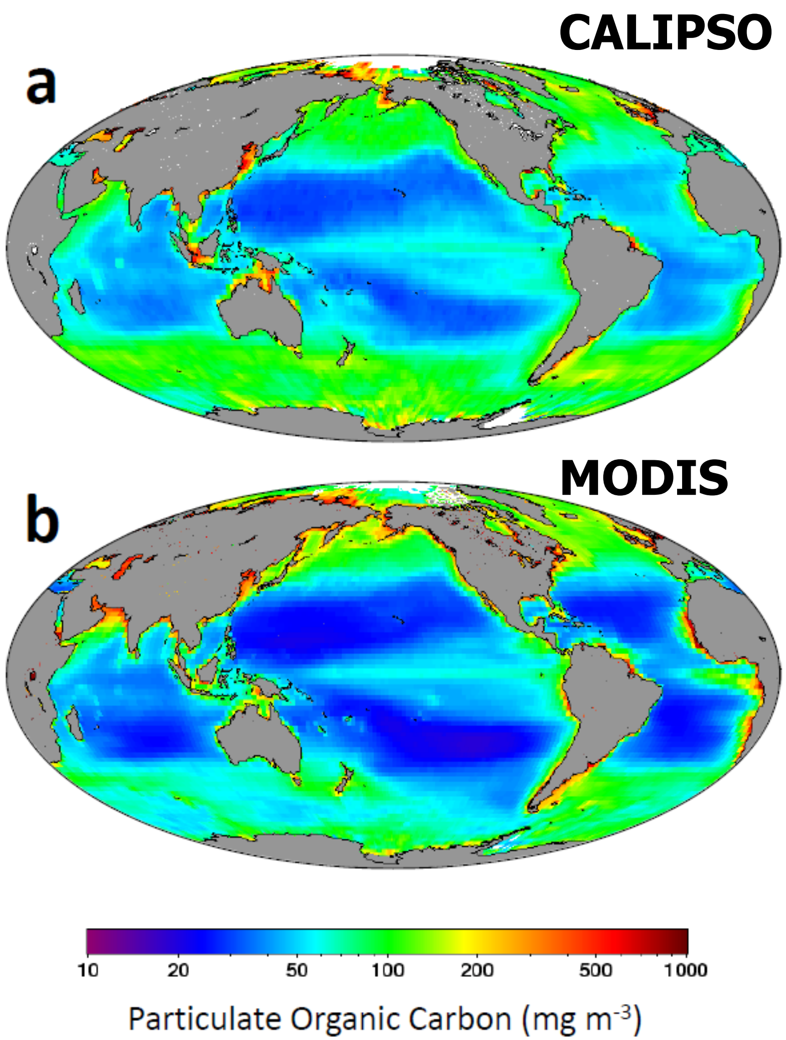


- Lidar microphysical retrievals of effective radius and concentration compare favorably to in situ measurements made during spirals of the DOE G-1 aircraft during the TCAP mission off Cape Cod, 2012

Airborne multiwavelength High Spectral Resolution Lidar (HSRL-2) observations during TCAP 2012: vertical profiles of optical and microphysical properties of a smoke/urban haze plume over the northeastern coast of the US
D. Müller, C. A. Hostetler, R. A. Ferrare, S. P. Burton, etc., accepted
Atmos. Meas. Tech. Discuss., 7, 1059-1073, 2014

Ocean Retrievals

Building on successes with CALIPSO

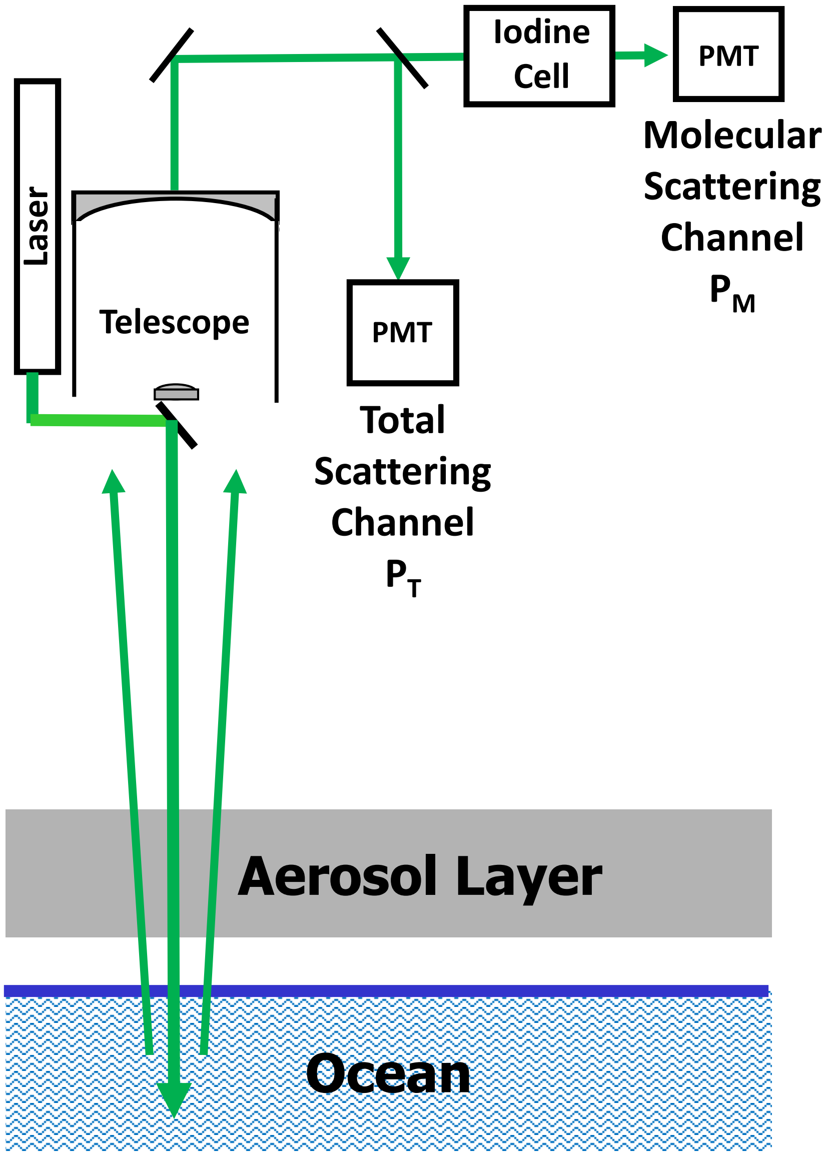


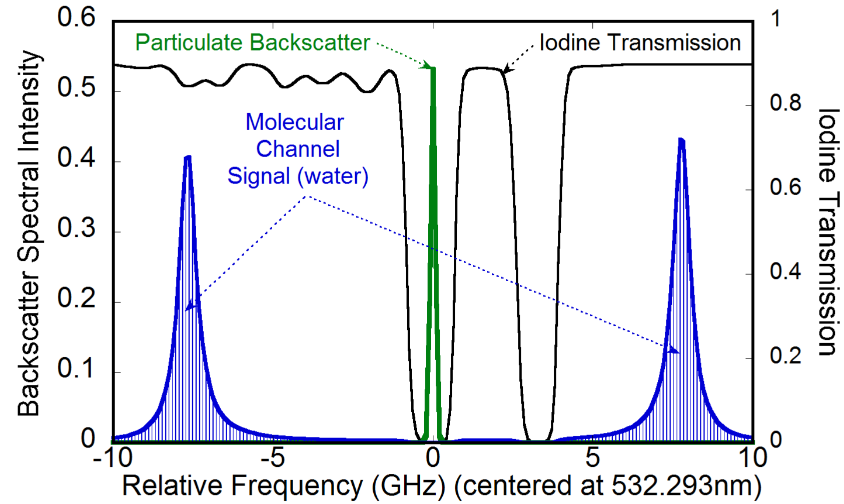
- Particulate Organic Carbon (POC) and plankton backscatter (b_{bp}) retrieved from CALIPSO spaceborne lidar compared favorably to MODIS product
- CALIPSO retrievals use employ vertically-integrated subsurface data, i.e., not vertically resolved

From: Behrenfeld et al., Space-based lidar measurements of global ocean carbon stocks, GRL, 2013

Data in each panel are climatological annual averages for the 2006 to 2012 period. Data are binned to 2° latitude by 2° longitude pixels.

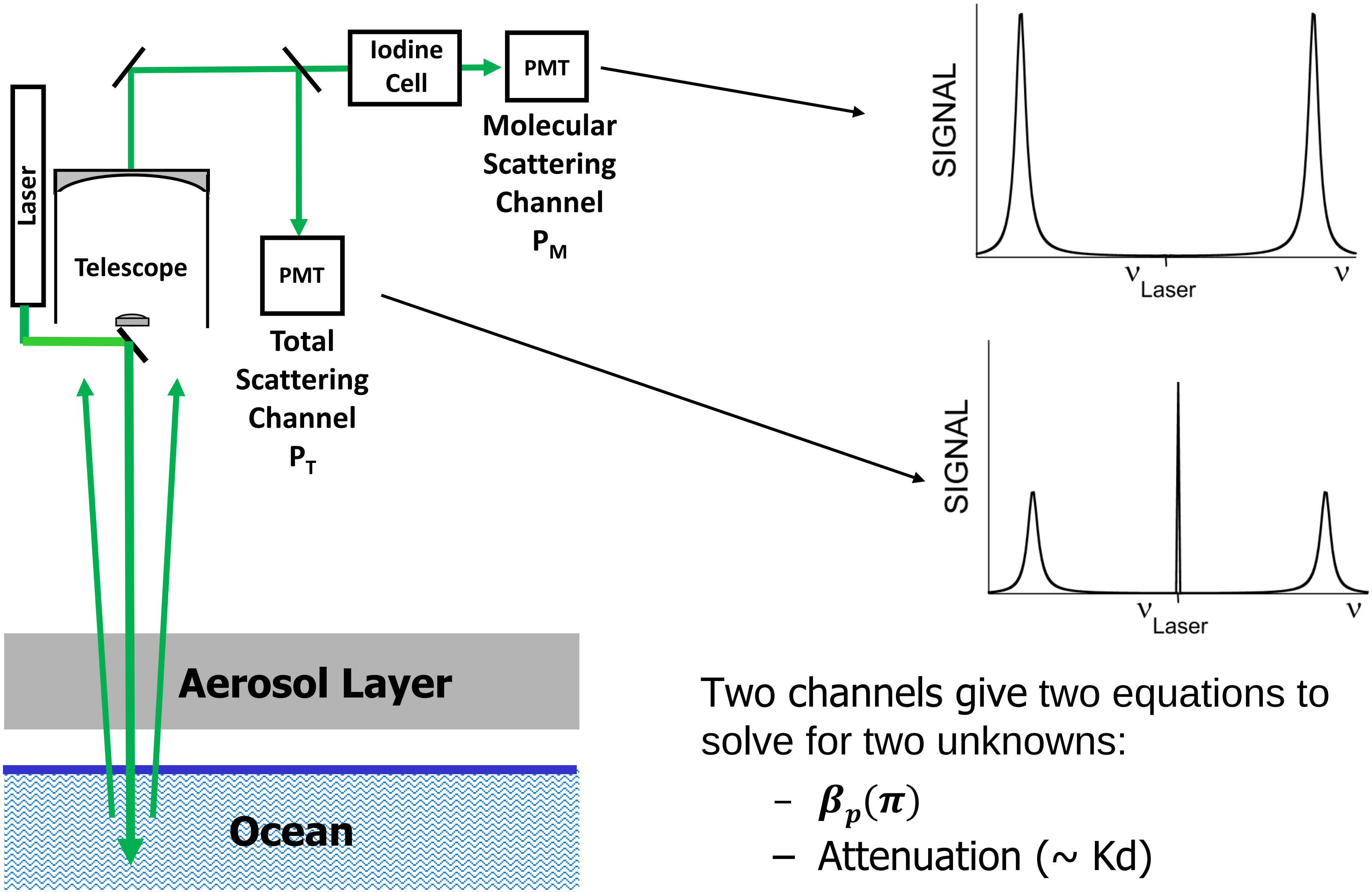
HSRL technique for ocean profiling





- Laser tuned to I2 absorption line
- Particulate backscatter blocked from "Molecular Channel"

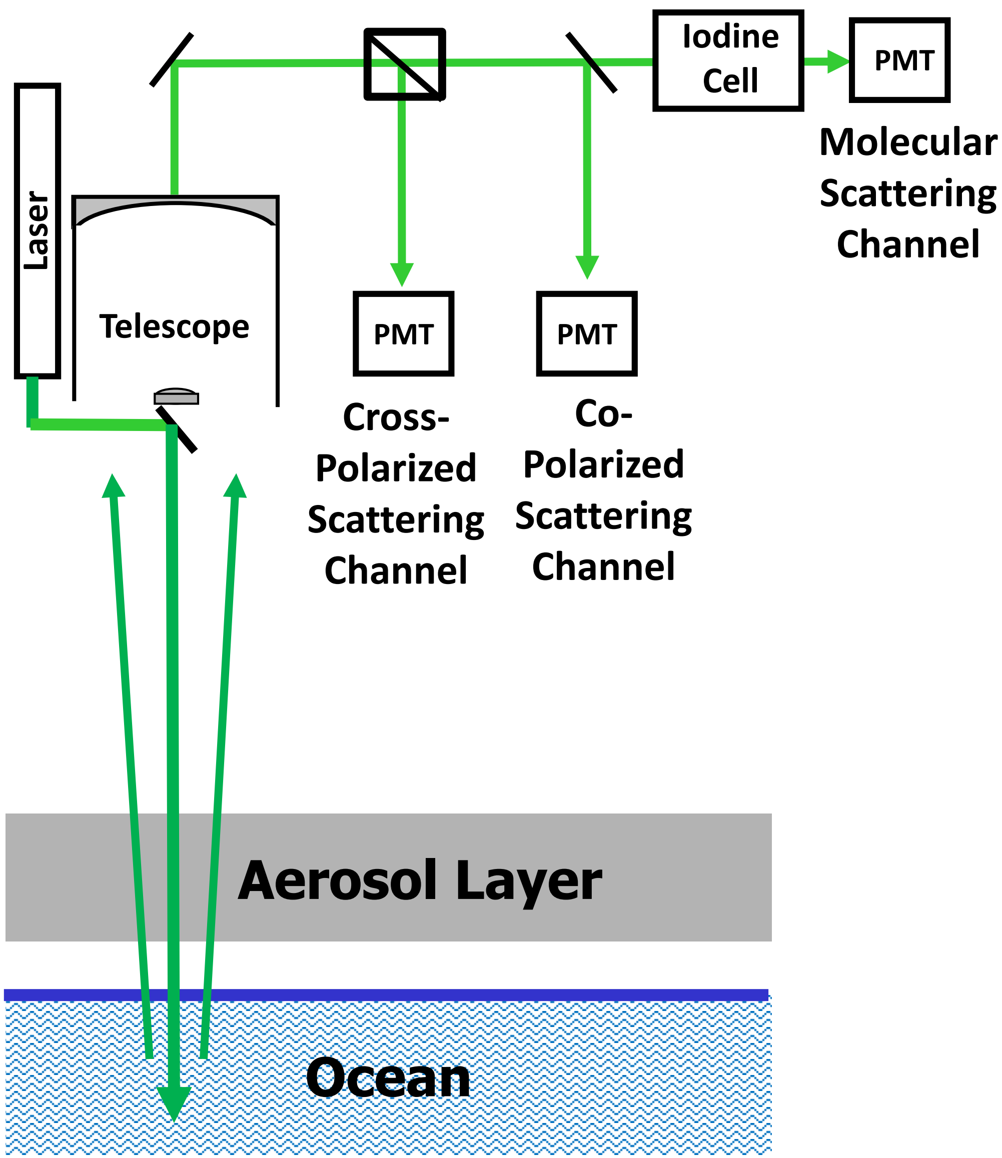
HSRL technique for ocean profiling



Two channels give two equations to solve for two unknowns:

- $\beta_p(\pi)$
- Attenuation (~ Kd)

Ocean HSRL data products



- b_{bp}
  - $\beta_p(\pi)$ determined from ratio of total backscatter to Brillouin backscatter
  - $\beta_p(\pi)$ scaled to bbp using assumption on phase function
- K_d (lidar attenuation)
  - Determined from derivative of molecular backscatter signal
- S_p
  - Lidar ratio: ratio of lidar attenuation to 180° backscatter $= Kd/\beta_p(\pi)$
- δ_p
  - Particulate depolarization determined from the ratio $\beta_p(\pi)$ of the cross-polarized to co-polarized channels

Ship and Atmospheric Bio-optics Research (SABOR) Mission: 18 July – 6 Aug

Objective: investigate the utility of lidar and polarimetery for future satellite ocean ecosystems missions

Ship Operations

- Univ. of Rhode Island R/V Endeavor
- Continuous underway measurements and 24 over-the-side stations
- Instruments:
  - 7 underway hyper/multi-spectral instruments
  - 4 over-the-side platforms with 20 hyper/multi-spectral instruments

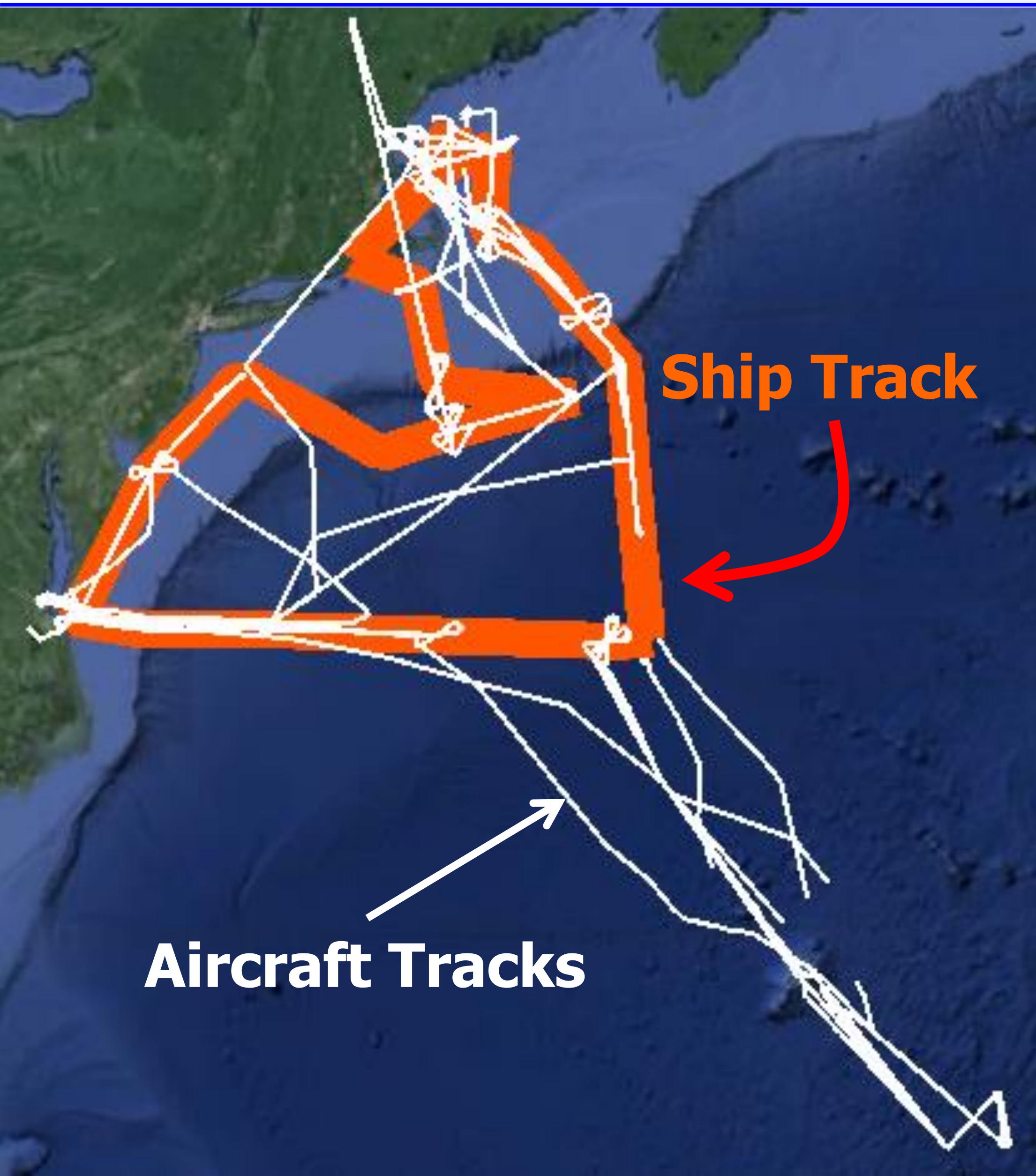
Aircraft Operations

- NASA Langley UC-12 aircraft
  24 science flights mostly coordinated with ship from bases in New Hampshire, Bermuda, & NASA Langley
- Instruments:
  - HSRL-1
  - Research Scanning Polarimeter (RSP)

Support: SMD Ocean Biology and Biogeochemistry Program

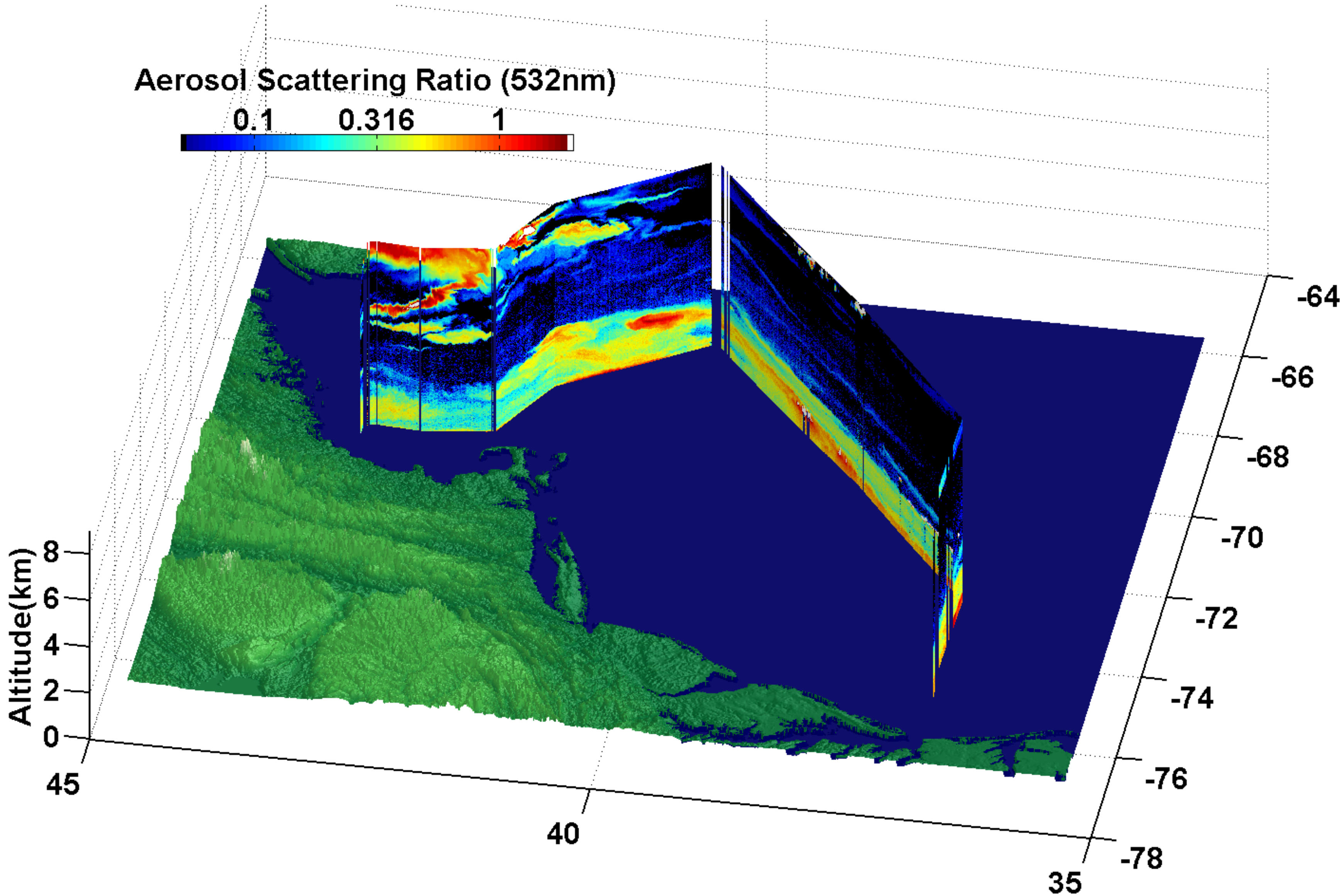
Partners: Oregon St Univ., Univ. of Maine, City University of NY, Wet Labs, Naval Research Lab, Sequoia, Bigelow, and others

Most SABOR flights coordinated with data acquisition on research vessel Endeavor

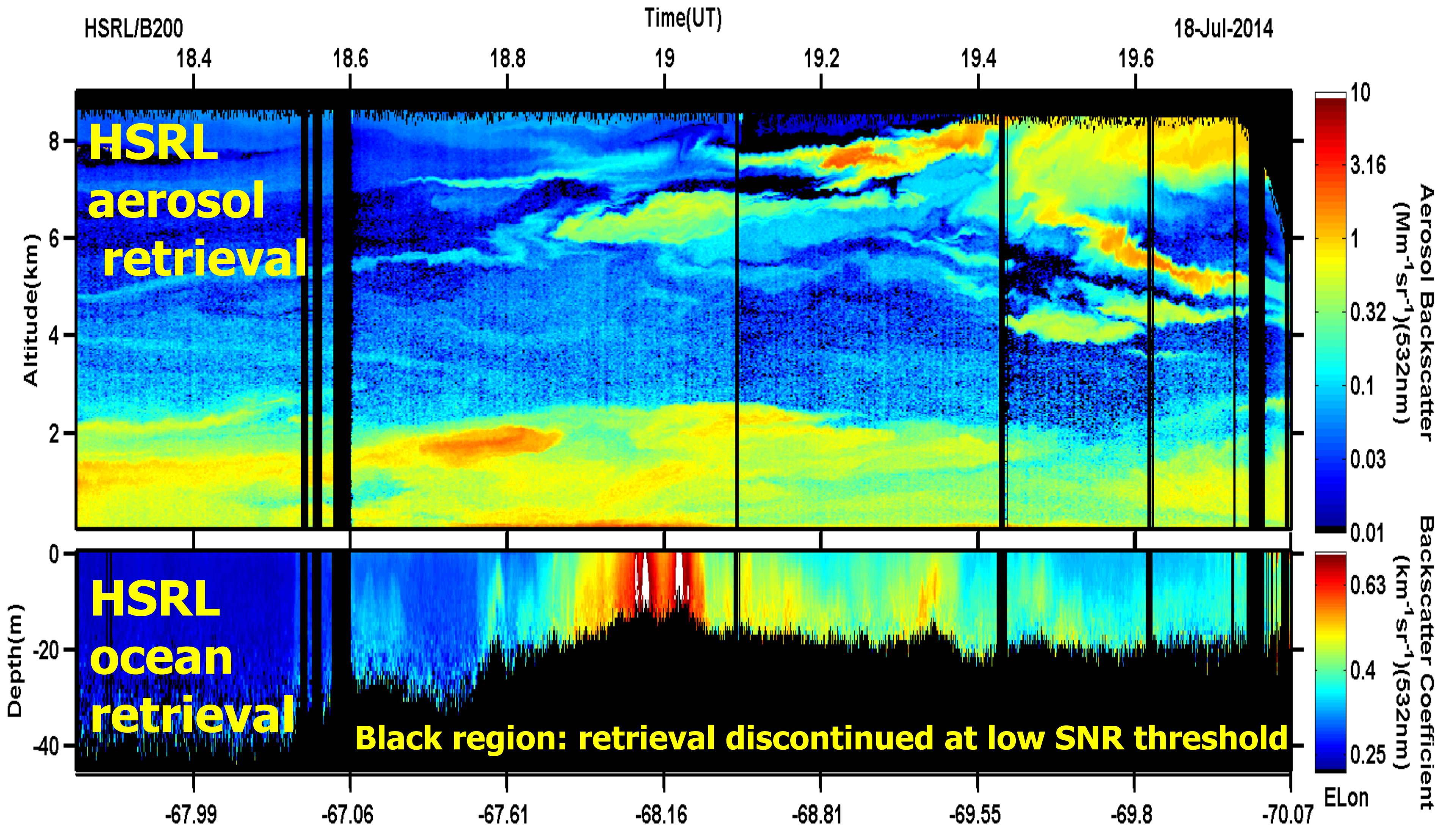


- Flights conducted largely along ship track
- Crossing patterns over the ship to acquire RSP polarimeter data at appropriate solar angles coincident with ship-borne polarimeter measurements

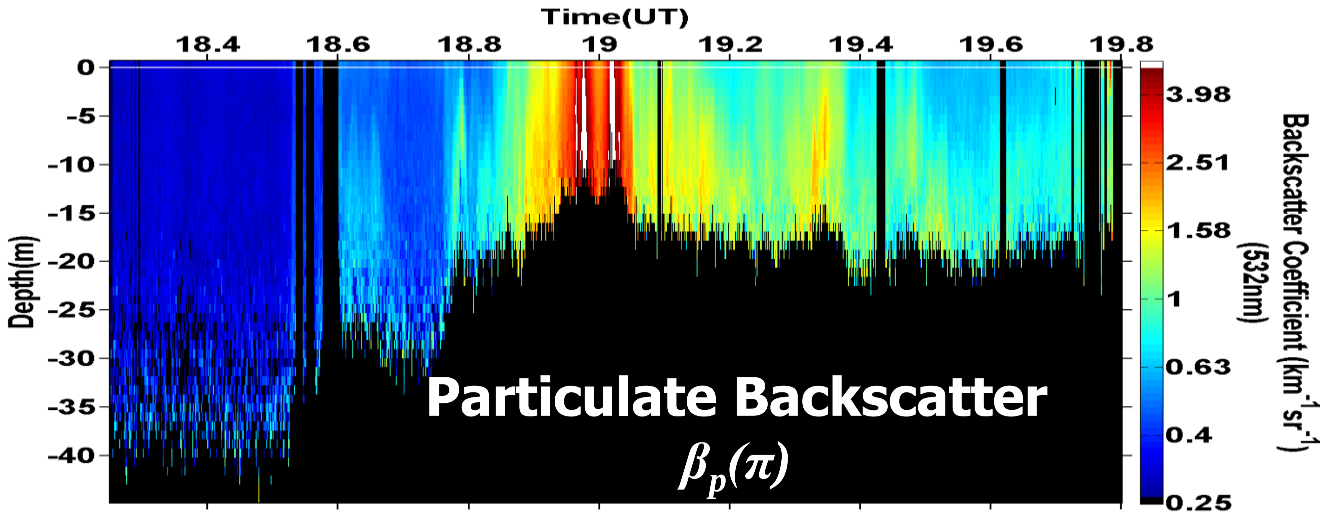
18 July transit flight

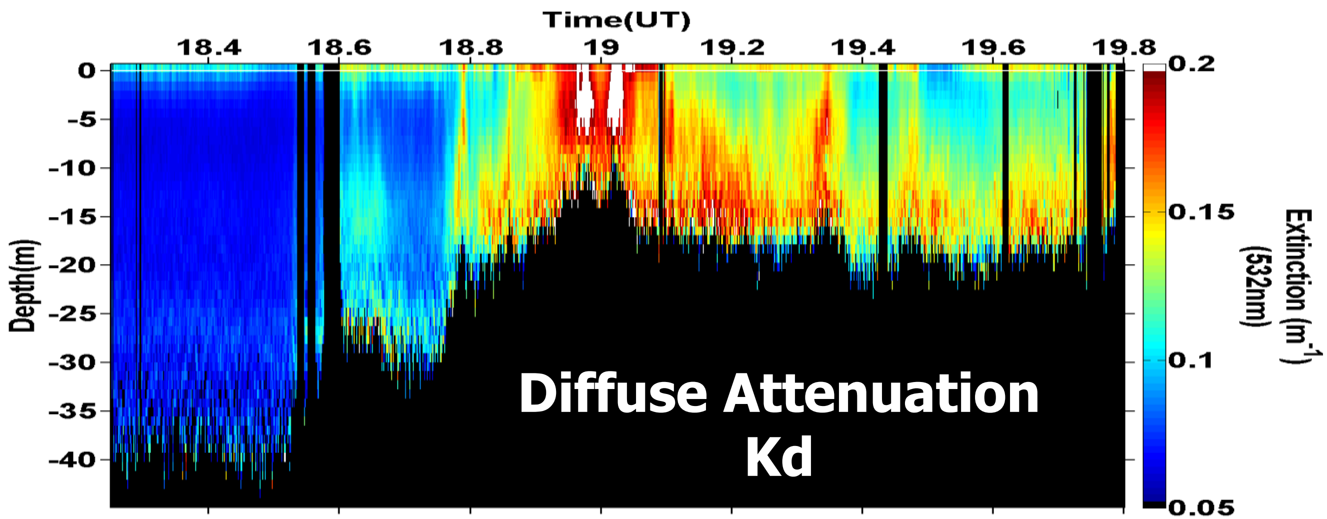


18 July flight: Unwrapped atmosphere and ocean curtains

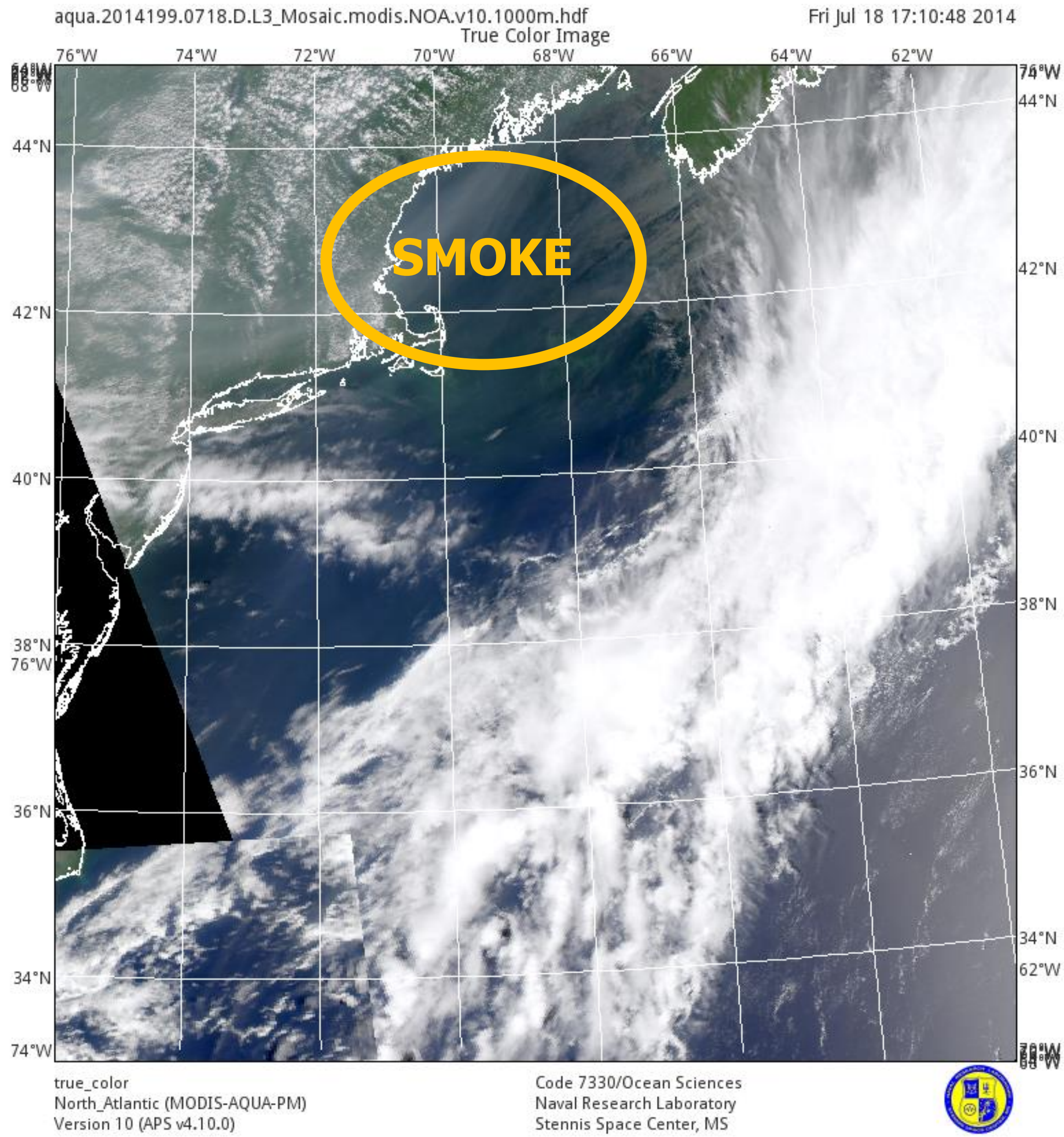


HSRL technique provides independent retrievals of particulate backscatter and attenuation



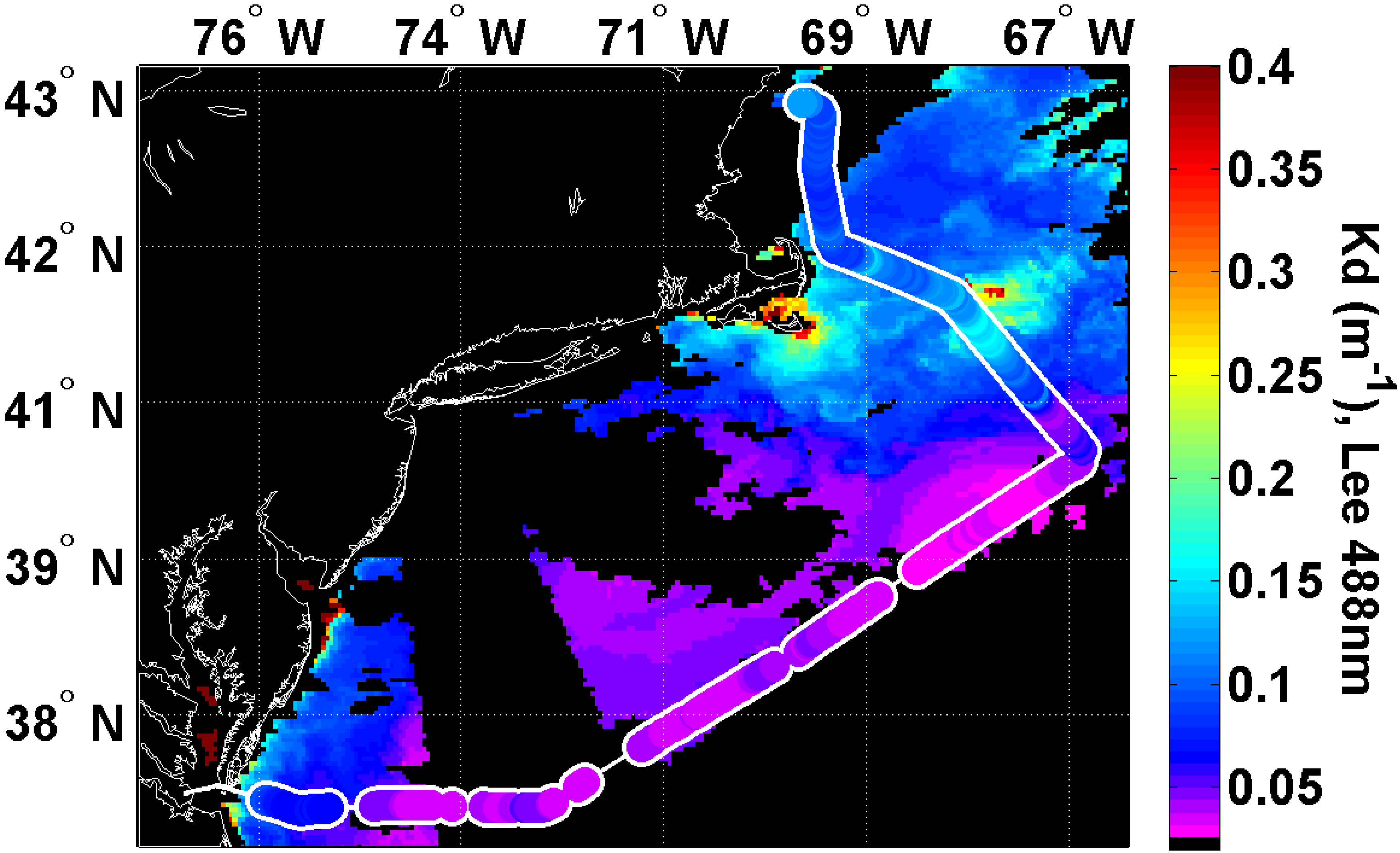


MODIS True Color Image



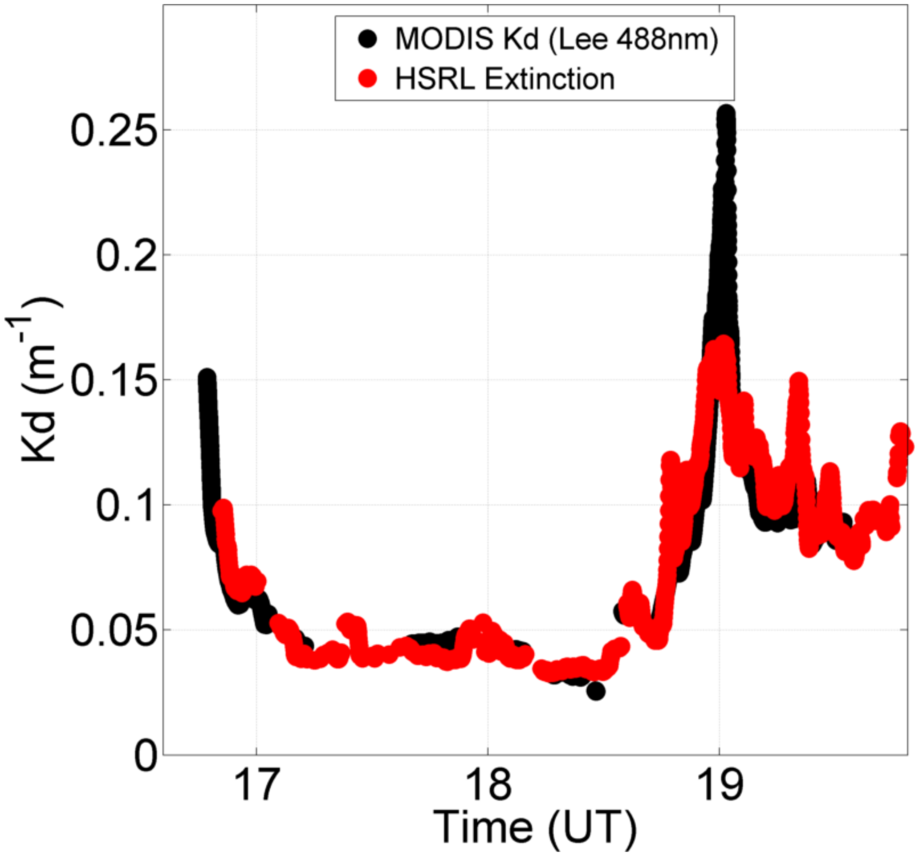
Imagery courtesy of Rick Gould

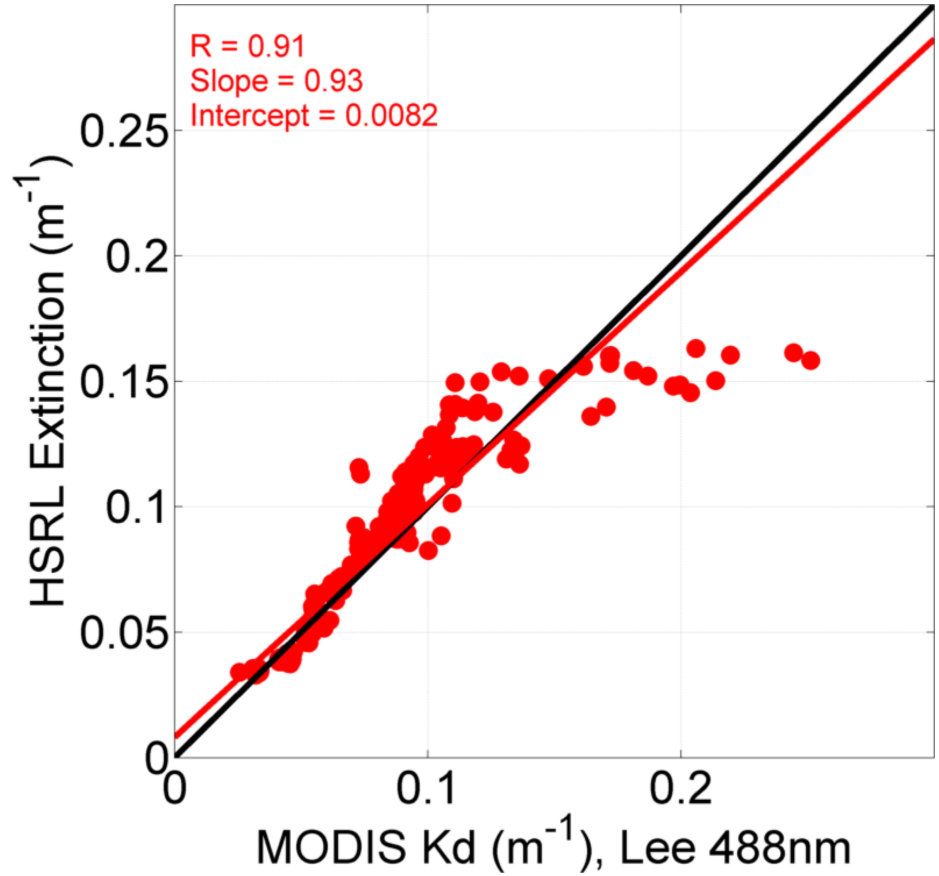
HSRL Kd overlaid on MODIS Kd488 Lee



The only modification to the HSRL Kd (532 nm) was adjustment for water absorption between 488 and 532 nm. No other conversions were attempted.

Comparison of HSRL Kd with Kd488 Lee

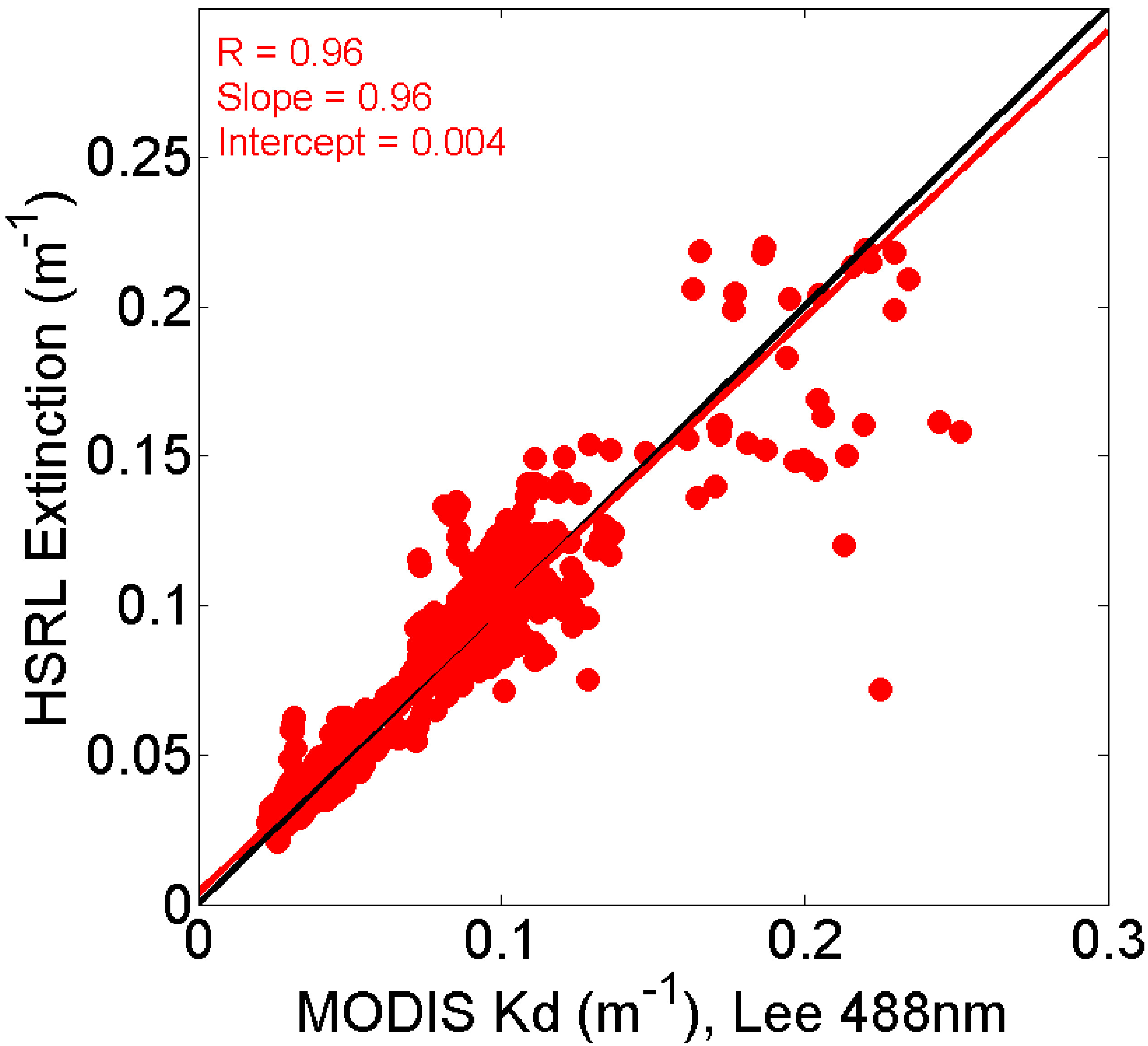




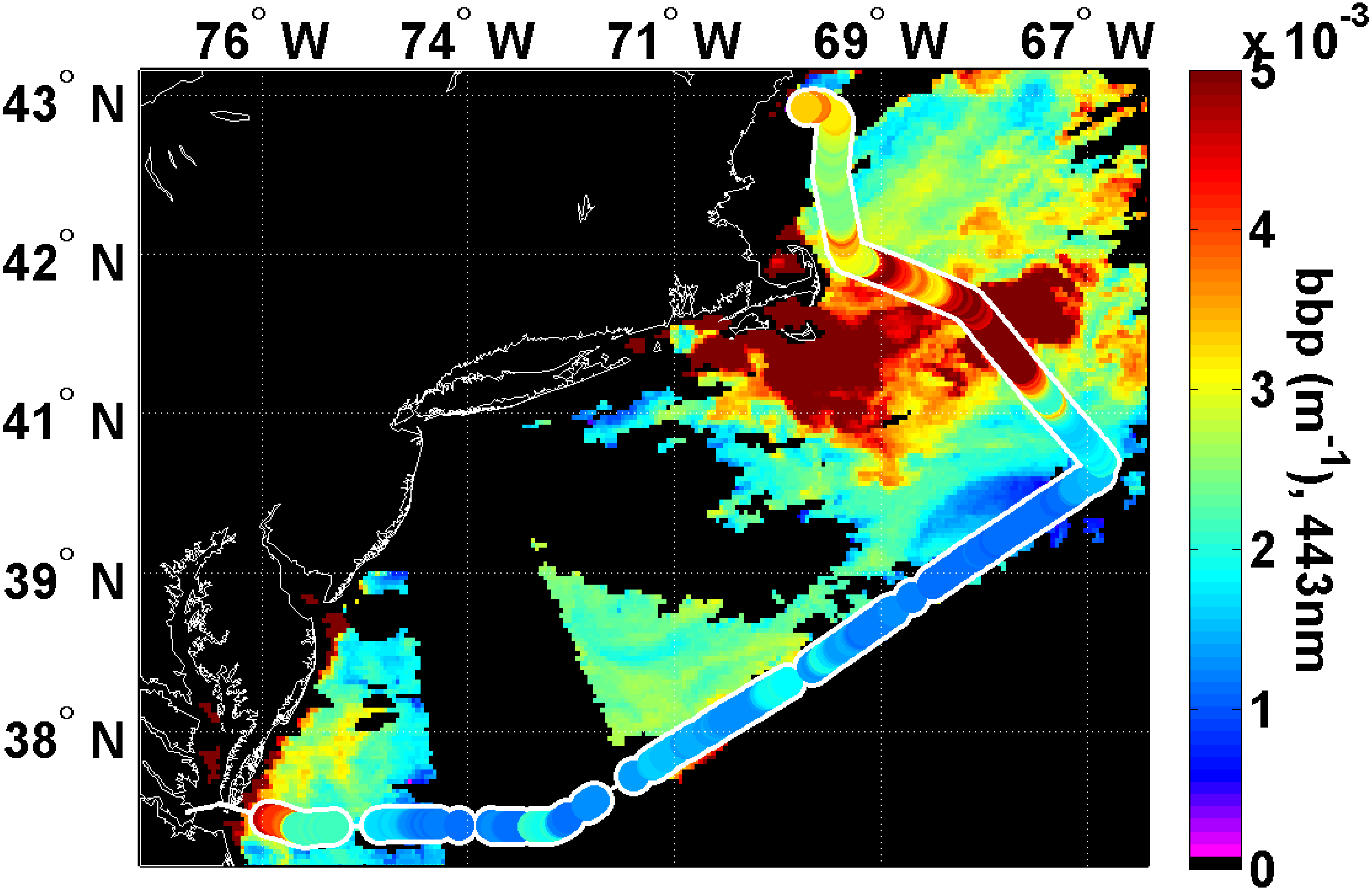
- HSRL (red) and MODIS (black) bbp along flight track
- Time axis is time at which lidar data were acquired.
- MODIS overpass at 17:13 UT

- High correlation
- Largest differences at peaked MODIS Kd in Georges Bank region

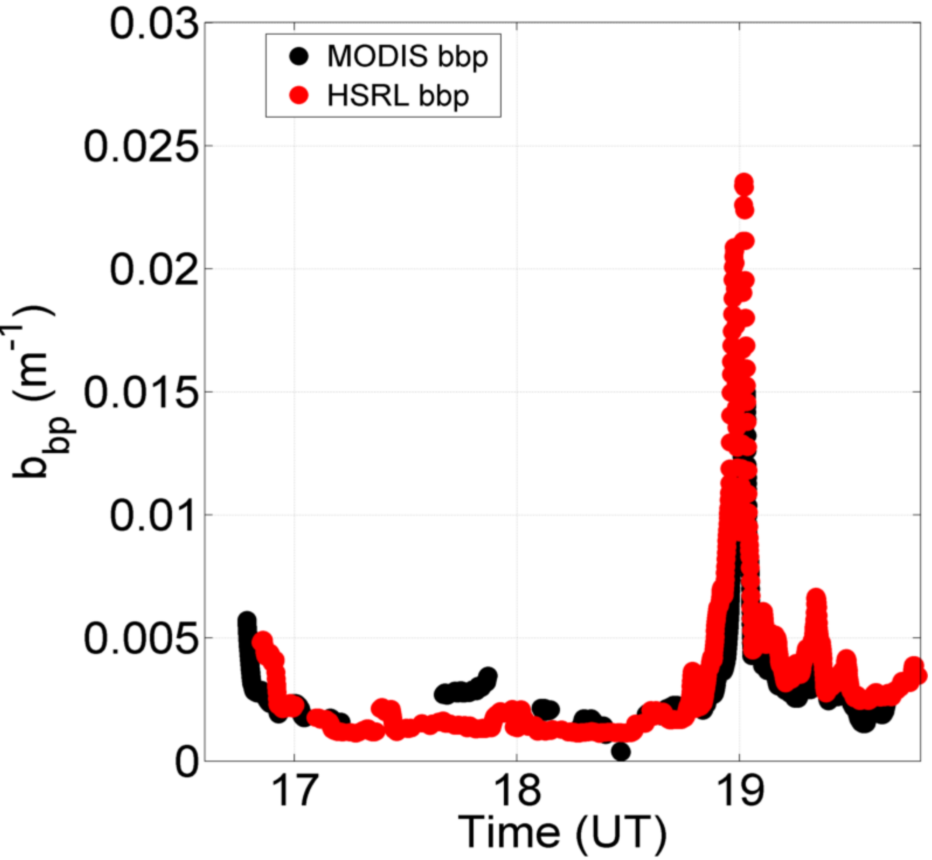
Comparison to all MODIS QAA Kd

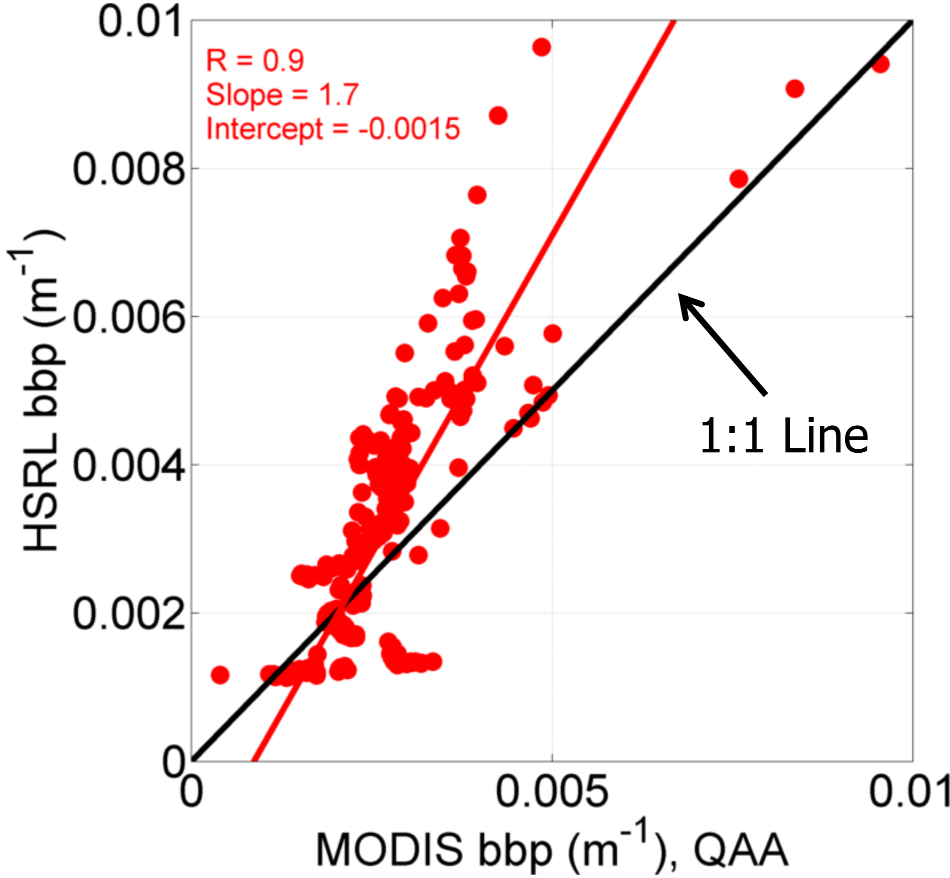


HSRL b_{bp} overlaid on MODIS b_{bp}



Comparison of HSRL b_{bp} with MODIS

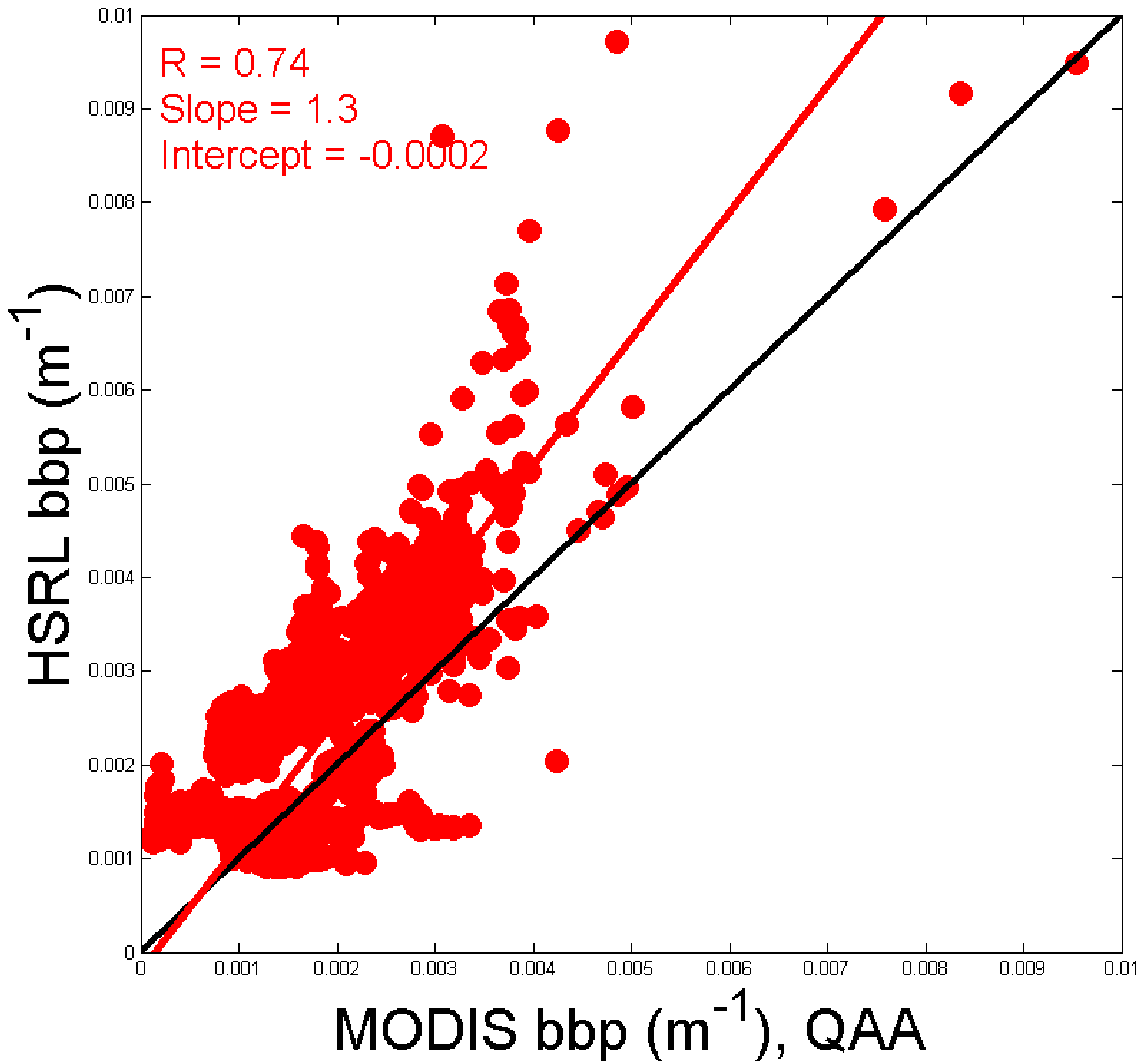




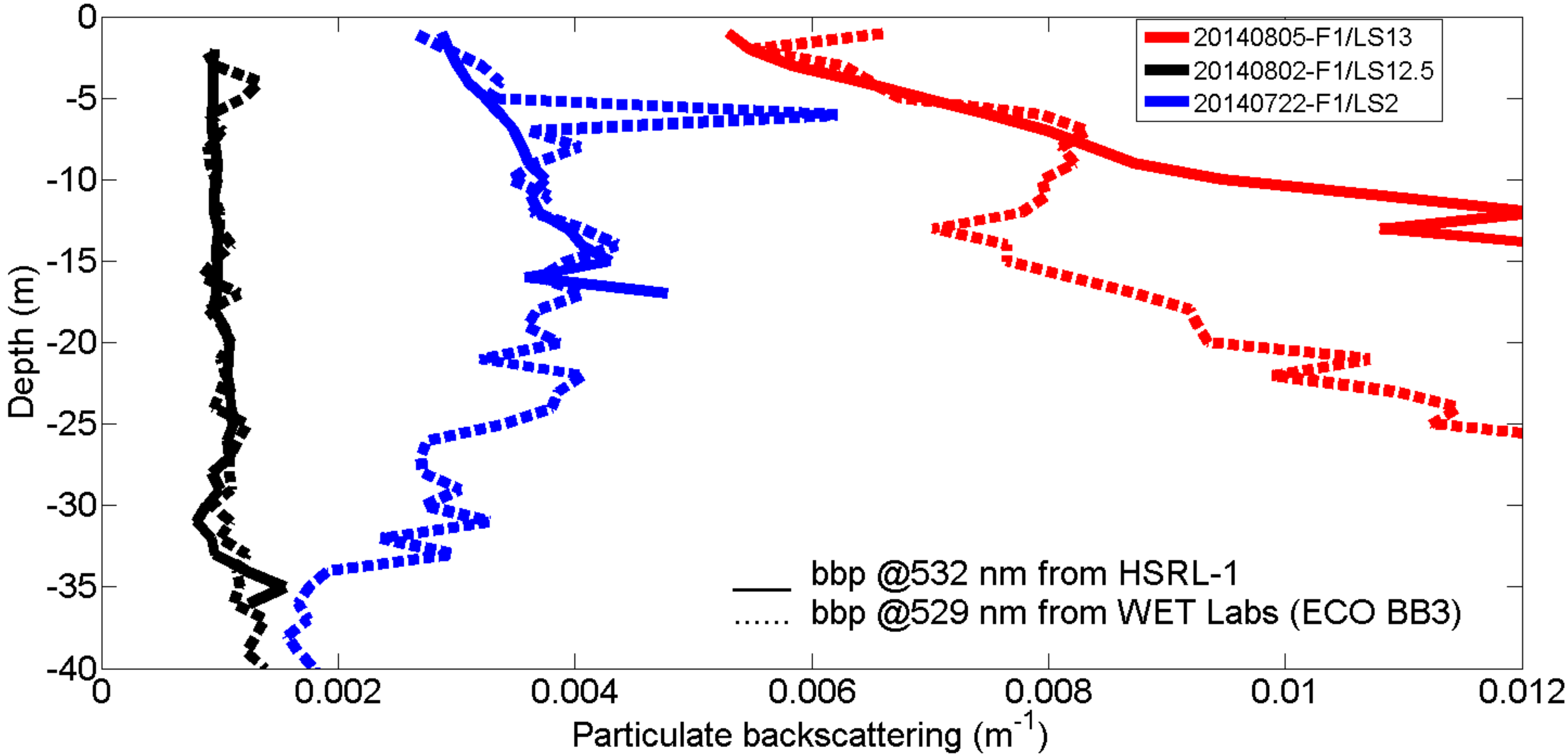
- HSRL (red) and MODIS (black) bbp along flight track
- Time axis is time at which lidar data were acquired.
- MODIS overpass at 17:13 UT

- High correlation
- Obvious scaling (1.7) and offset (0.0015 m^{-1}) differences

Comparison to all MODIS QAA b_{bp}

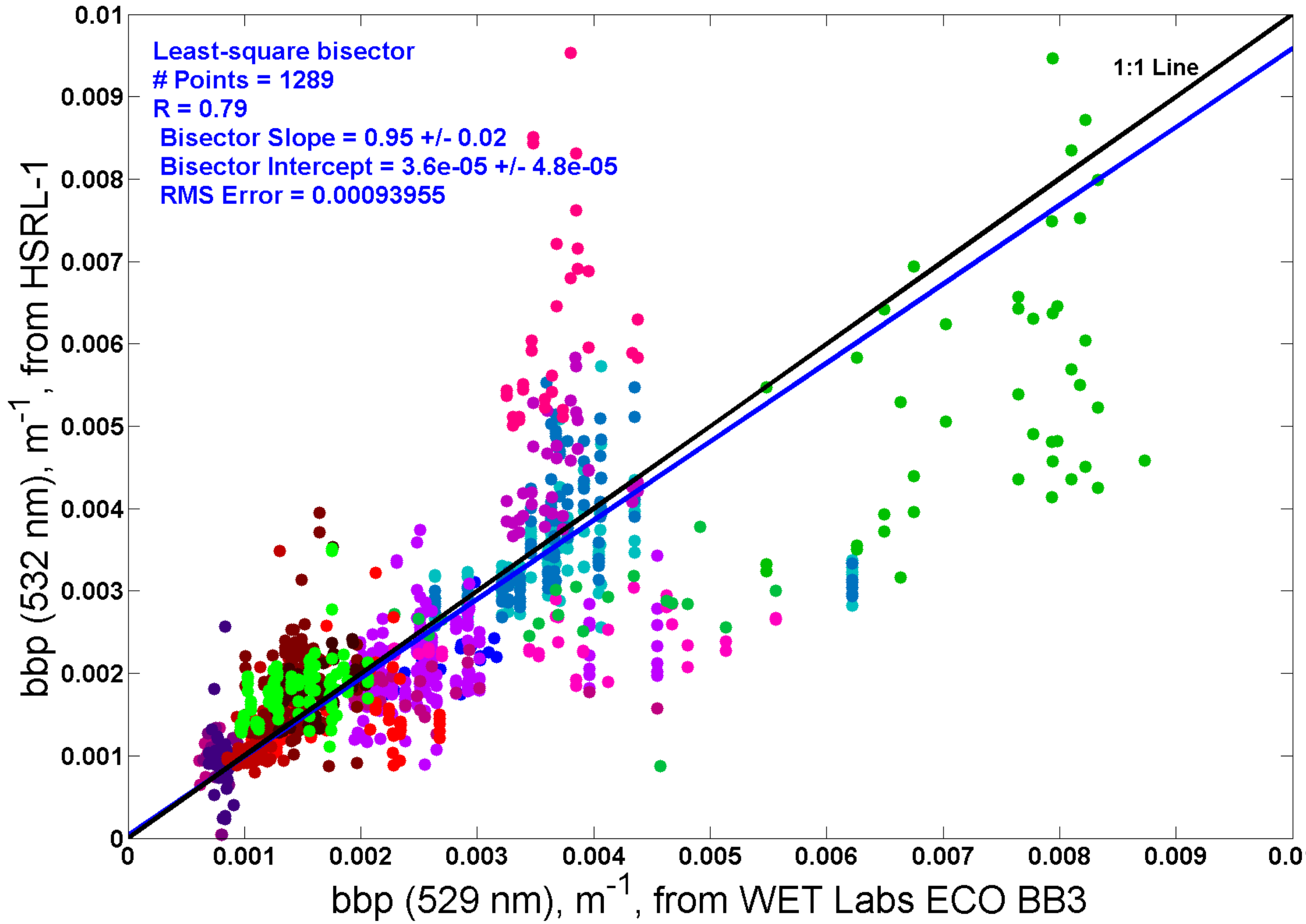


Selected b_{bp} profile comparisons showing dynamic range encountered on SABOR



SABOR profile data courtesy of Ivona Cetinic, Nicole Stockley, and Mike Twardowski

HSRL b_{bp} shows high correlation with in situ profile data from 13 SABOR castings

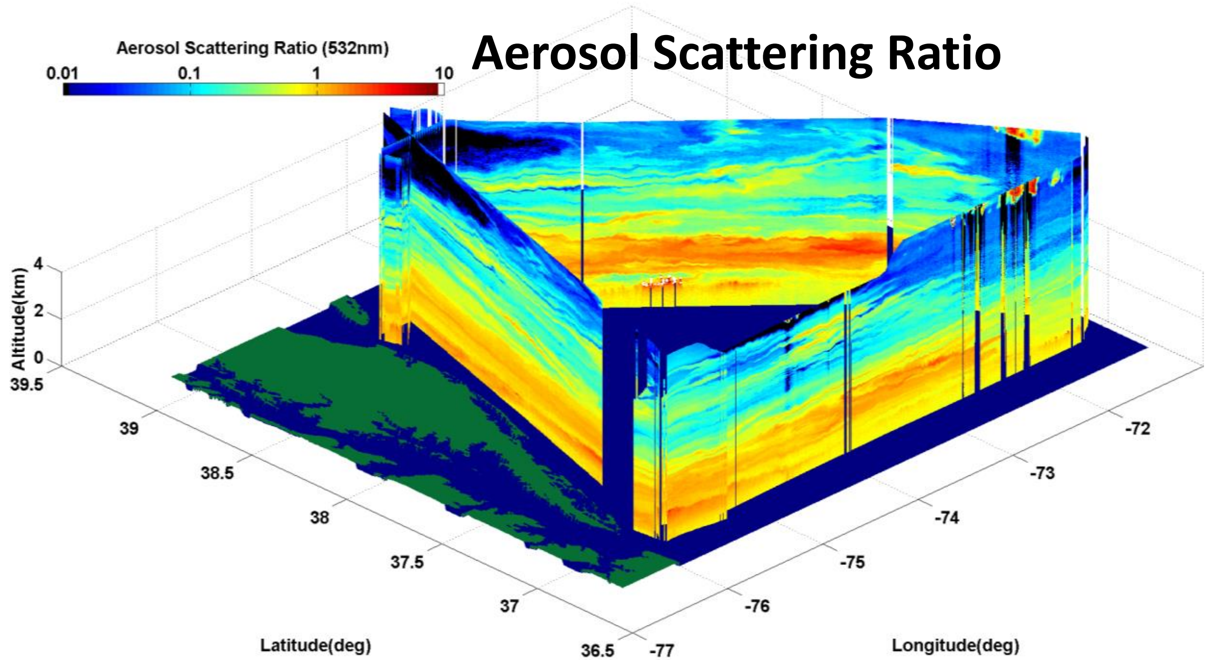


Conversion of 180° lidar backscatter, $\beta(\pi)$, to b_{bp}:

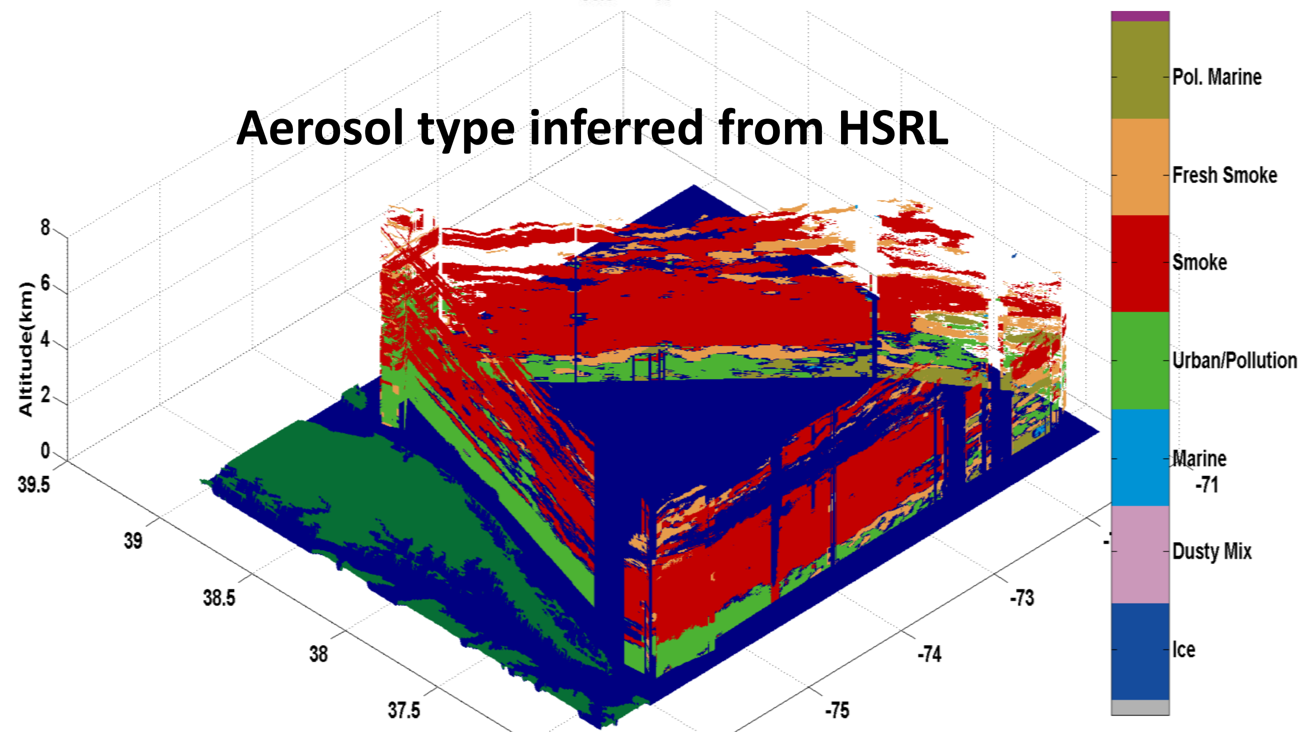
$$b_{bp} = \chi_p\,(2\pi)\,\beta(\pi) = 0.5\,(2\pi)\,\beta(\pi)$$

SABOR profile data courtesy of Ivona Cetinic, Nicole Stockley, and Mike Twardowski

Aerosol Scattering Ratio



Aerosol type inferred from HSRL

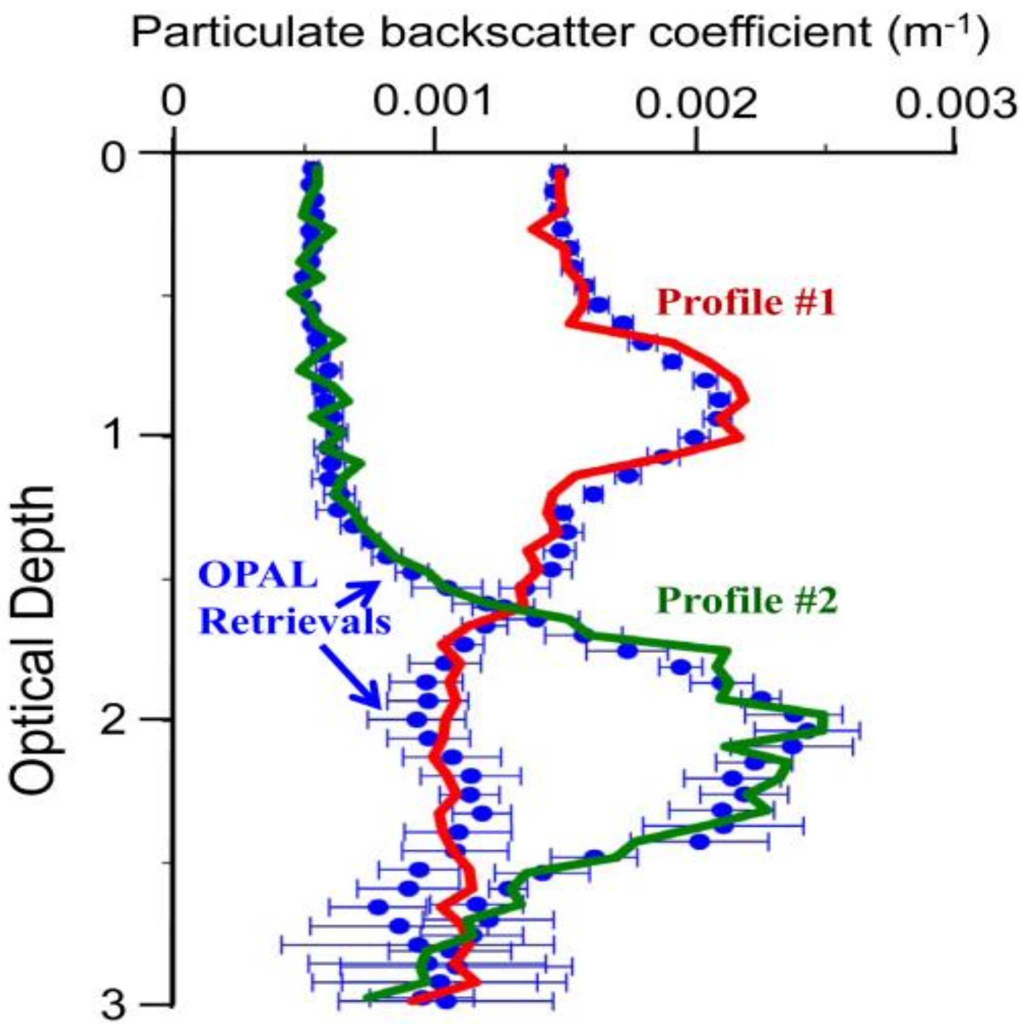


Complex aerosol environment on SABOR

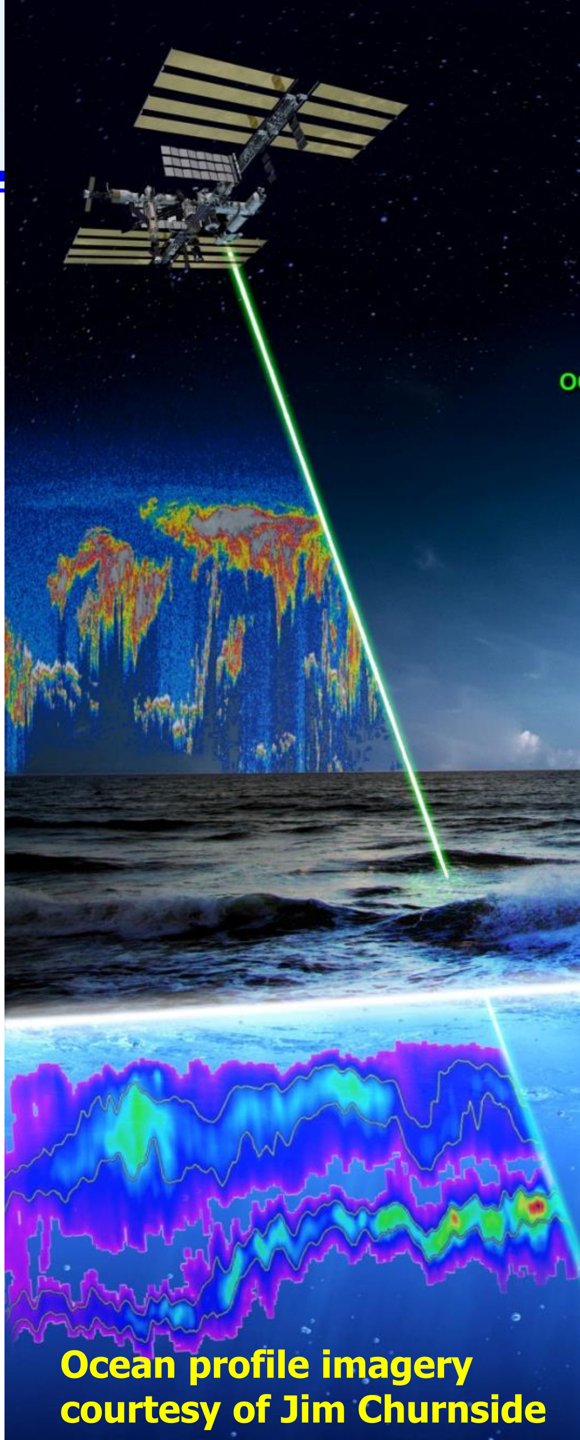
- Aerosol optical depths were very high, sometime exceeding 0.5
- HSRL aerosol typing algorithm often indicated a layer of smoke over a layer of continental pollution
- Lidar observations could be useful for understanding aerosol influences on ocean color retrievals
- Joint ocean-atmosphere retrievals using lidar + polarimeter/ocean color radiometers may increase accuracy in both regimes.

Spaceborne Ocean-Optimized HSRL

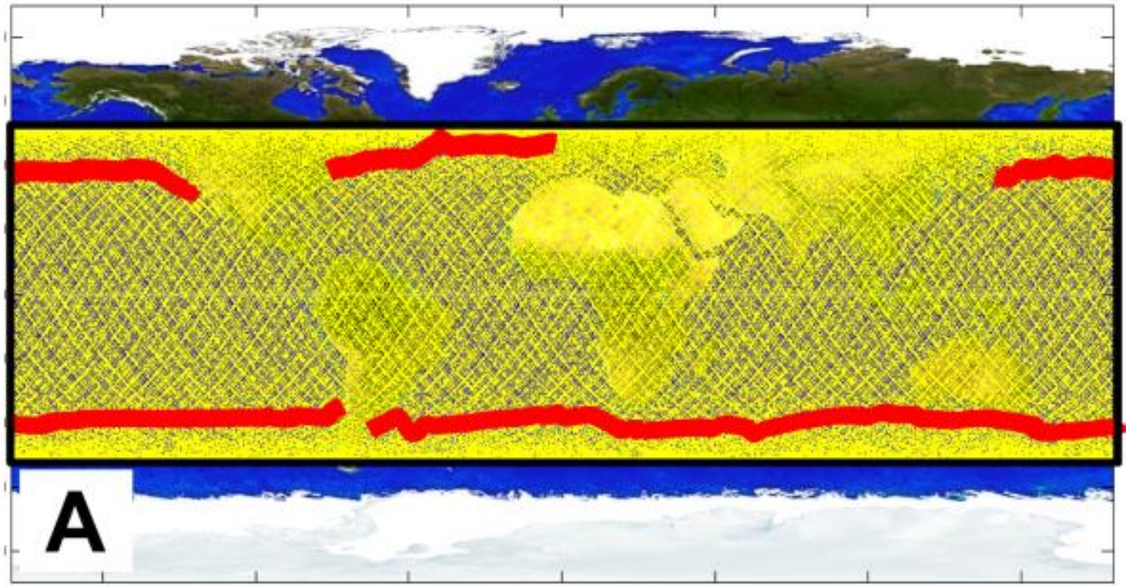
Ocean Profiling and Atmospheric Lidar (OPAL)



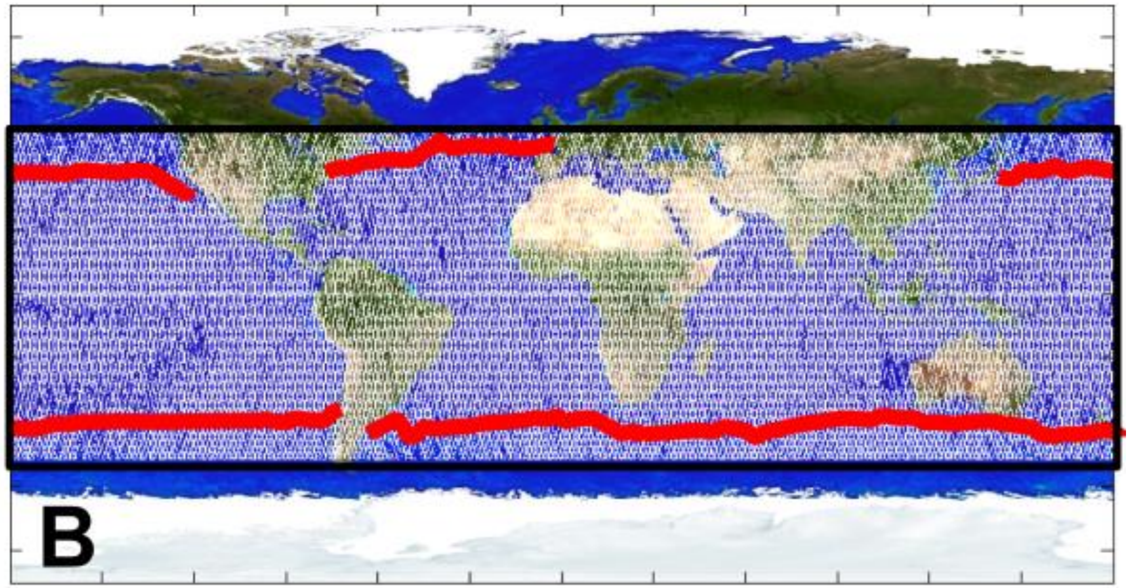
- Truth profiles in solid lines
- Simulated retrieval with 1-σ uncertainties in blue



Sampling example: OPAL on ISS



ISS orbit tracks over 1-month period



CALIPSO track locations where atmospheric optical depth < 1. Shows OPAL yield including cloud interferences

Benefits of spaceborne ocean lidar

- Improved quantification of biomass in oceans by resolving the variability of particulate backscatter with depth
- Significantly reduced uncertainties in ocean productivity by
  - Resolving the vertical distribution of phytoplankton
  - Resolving the vertical distribution of light for photosynthesis
  -
- Cross-integration between ocean biology and physical oceanography via observations of layering related to ocean physics.
- Day/night observations of chlorophyll fluorescence for assessing ecosystem health (e.g., iron stress)

Benefits of spaceborne ocean lidar

- Much more direct retrievals of bbp and Kd than passive ocean color instruments: would be used to assess and improve passive retrievals across entire swath of PACE or

- Provides measurements in scenes difficult for passive ocean color sensors
  - Broken cloud systems (cloud shadows, cloud 3-D effects)
  - Under tenuous cirrus and high aerosol loading

- Provides measurements at high latitudes inaccessible to passive techniques.

Summary

- Aerosol and ocean measurement objectives drive the design of next-generation spaceborne lidars
- Airborne prototype instruments have begun demonstrating both measurements and advanced retrievals
  - Retrievals will improve in combination with passive sensor data, e.g., polarimeter
- Ocean lidar is feasible from satellite and would be a transformative measurement for ocean ecosystem studies

Thanks for your attention and to all that contributed to this presentation

Backup Charts

Cloud Retrievals

CALIPSO CALIOP cloud products enhanced via HSRL technique

Production

1. Cloud occurrence
2. Cloud height
3. Ice/water phase
4. ✓ Extinction profile and optical depth
   - Two retrievals: constrained by two-way transmittance or using modeled lidar ratio
5. ✓ Ice water content and path

Enhanced by HSRL Measurements

Experimental

1. ✓ cloud droplet nuclei concentration
2. ✓ cloud-top extinction (water clouds)

Lidar-based cloud microphysics retrievals in hazy skies

HSRL-measured depolarization (δ)

$$\delta = f(\alpha, R_e)$$

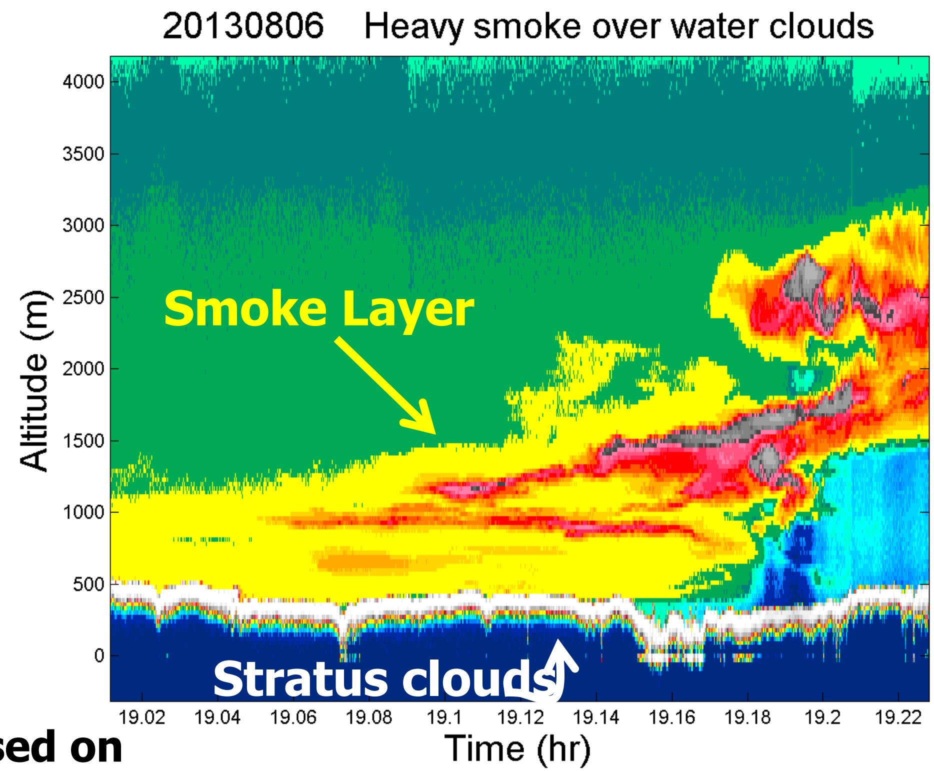
α : *HSRL-measured extinction*

R_e : *effective radius retrieved from passive sensor data*

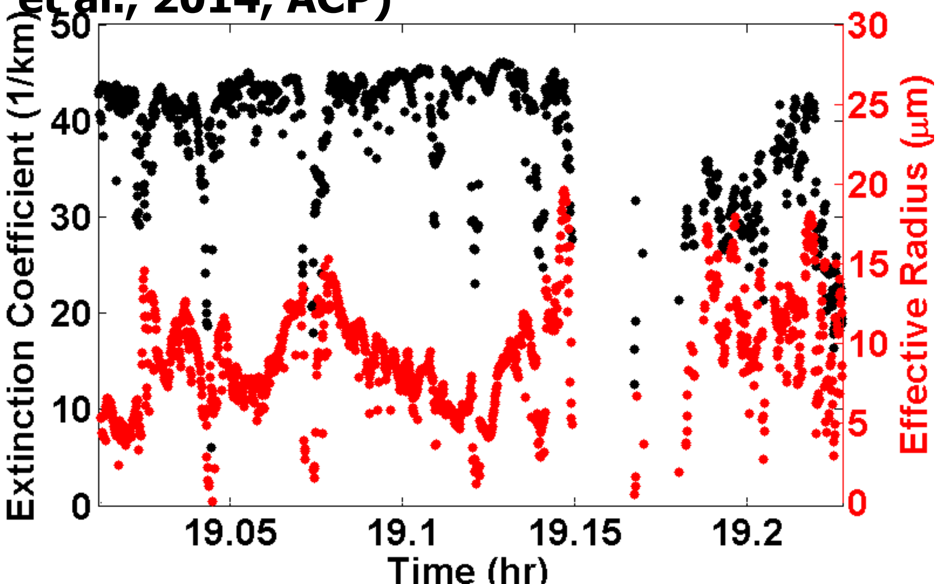
$$LWC = f(\alpha, R_e)$$

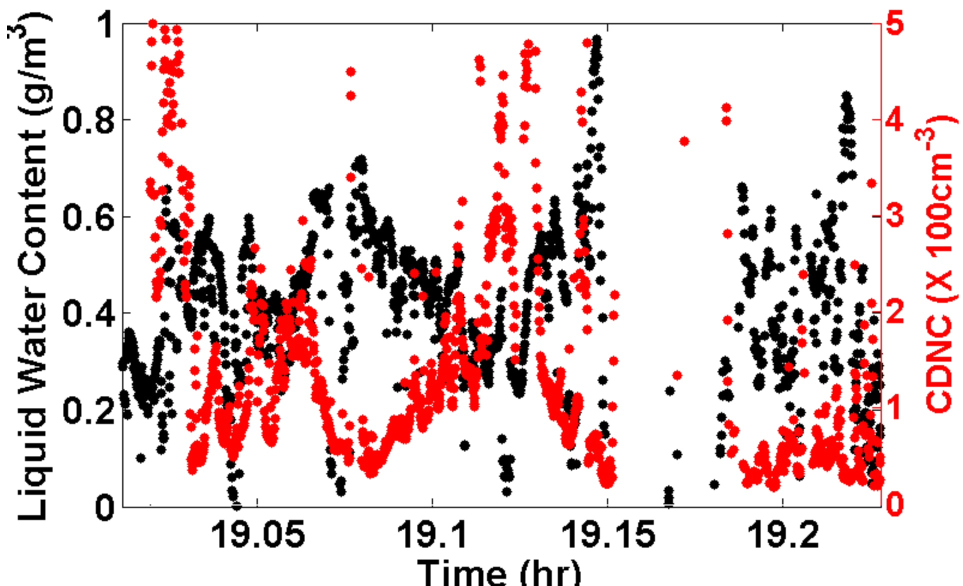
$$CDNC = f(\alpha, R_e, variance(R_e))$$

measured; *retrieved*; *assumed*

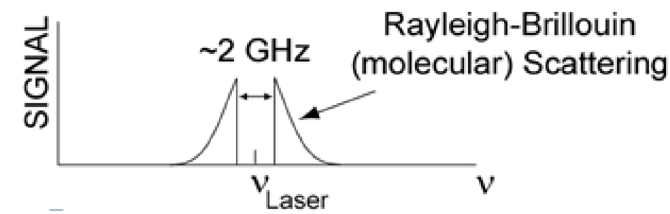


New results courtesy of Yongxiang Hu based on Hu et al., 2007, ACP; Li et al., 2011, ACP; Zeng et al., 2014, ACP)

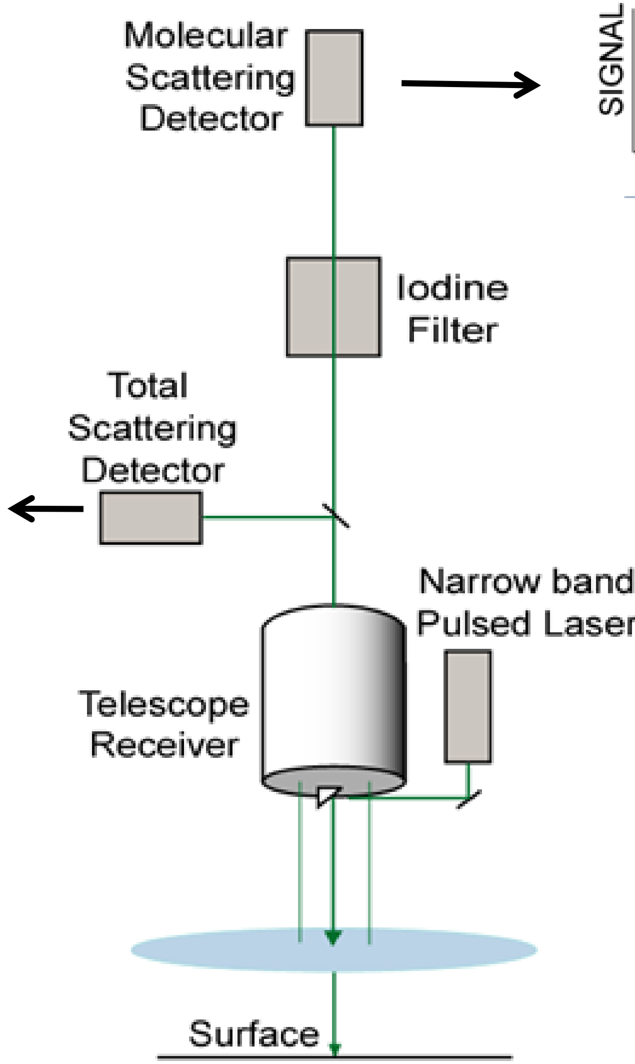


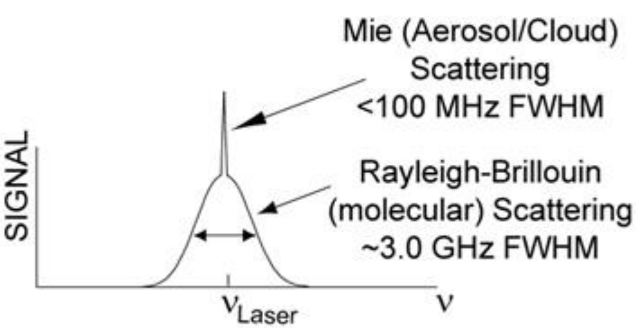


High Spectral Resolution Lidar (HSRL)



By tuning the laser to an iodine gas absorption line, this channel measures only the broadened molecular backscatter (the particulate backscatter is absorbed by the iodine gas).





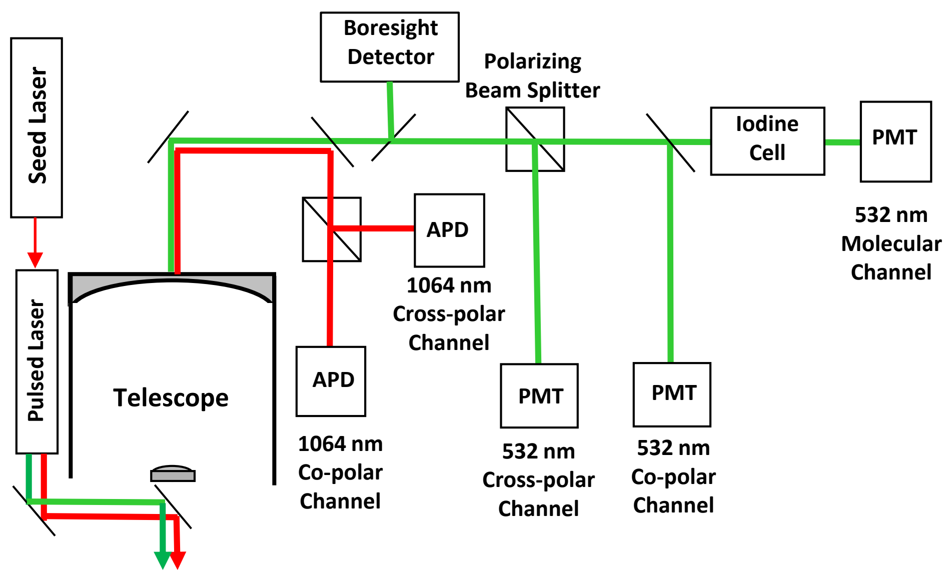
This channel measures the full spectrum of backscatter, including the particulate (Mie) backscatter and the broadened molecular backscatter

The 2 channels provide 2 equations to solve for 2 unknowns:
- **aerosol extinction**
- **aerosol backscatter**

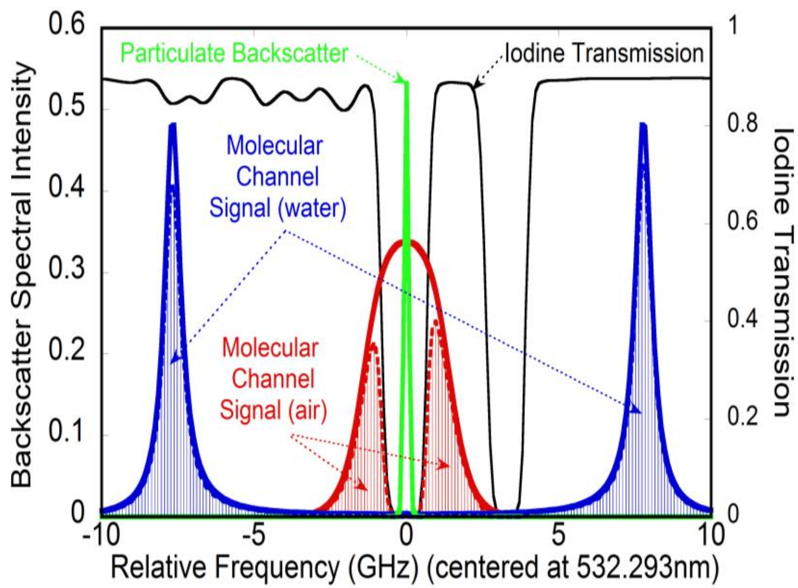
The “iodine technique” applies to 532 nm; interferometric approaches can be used at any wavelength.

Advantages of HSRL technique for atmospheric profiling also apply to ocean

Airborne HSRL-1 Block Diagram



Spectra of transmitted and received light



- Molecular backscatter from water molecules is dominated by Brillouin backscatter, which is shifted by ~ 8 GHz
- HSRL technique allows independent estimate of Brillouin and total backscatter
- Enables retrieval of attenuation and particulate backscatter

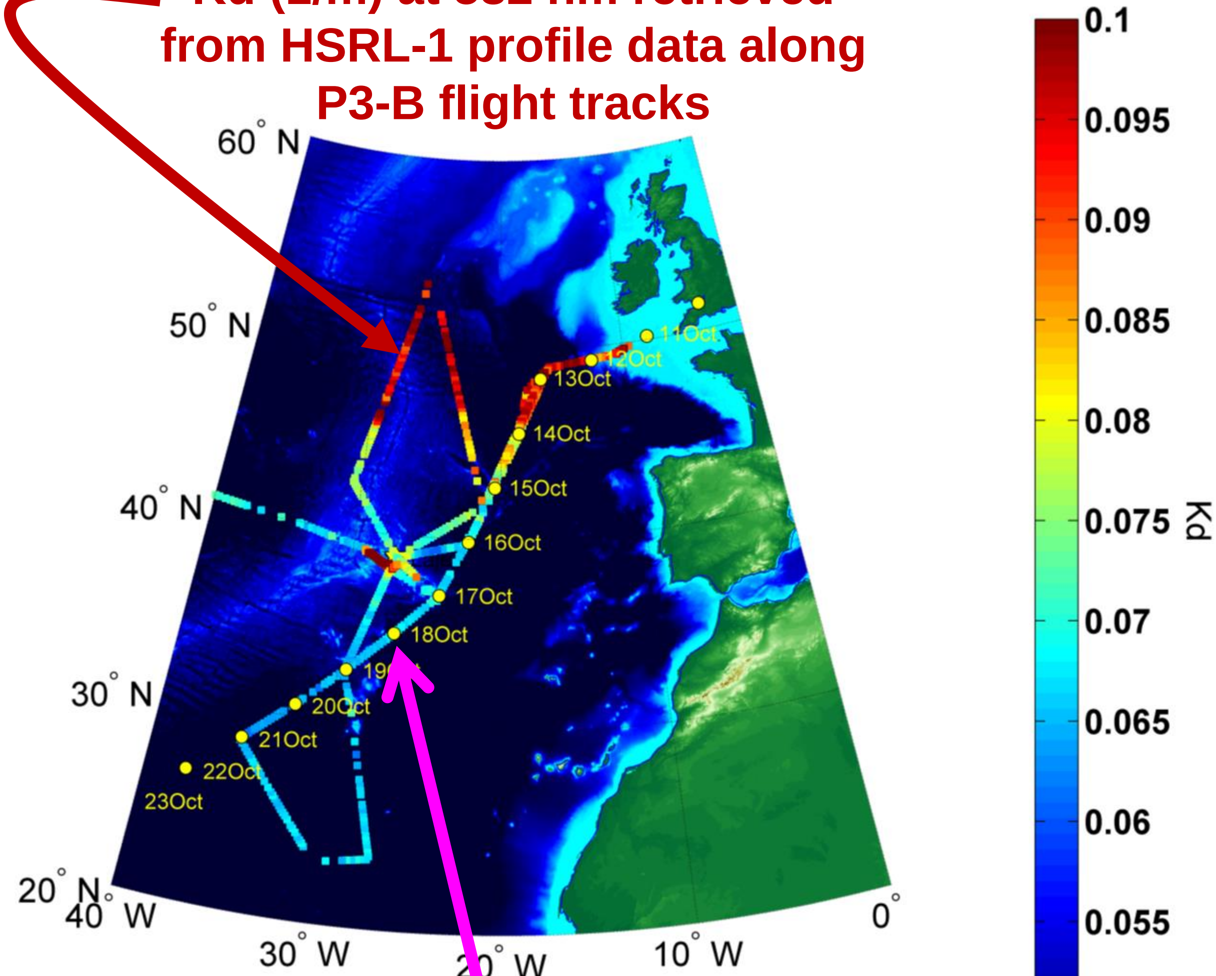
Ship-Aircraft Bio-Optical Research (SABOR) mission

The SABOR mission ended 6 August. Shown in next few charts are field-processed data products: calibration and retrieval assessment is ongoing.

SABOR builds on experience gained on Azores 2012 mission

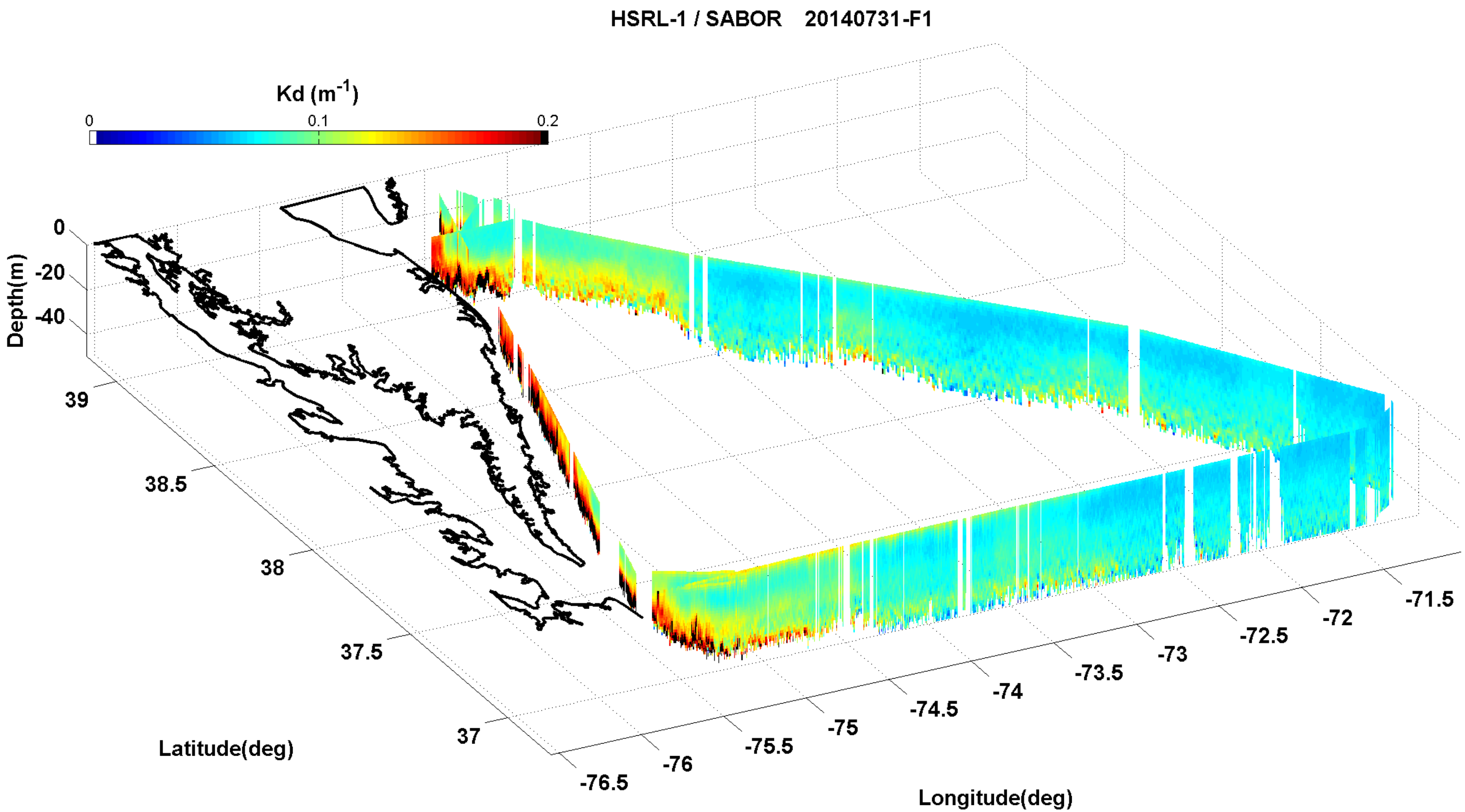
- Azores 2012 mission was first-ever application of HSRL technique for ocean profiling
  - Advantages of HSRL technique for atmospheric retrievals also apply to ocean profiling
  - HSRL-1 modified for 1-m vertical sampling under AITT program
  - Measured profiles to >50 m depth
- HSRL-1 ocean retrievals:
  - Kd (1/m): diffuse attenuation (shown)
  - b_{bp} (1/m): hemispheric backscatter from phytoplankton (in progress)
- RSP ocean retrievals
  - a_{CDOM} (1/m): absorption by colored dissolved organic matter
  - Surrogate for ocean color measurements to tie HSRL-1 retrievals to long-term ocean color record

Kd (1/m) at 532 nm retrieved from HSRL-1 profile data along P3-B flight tracks



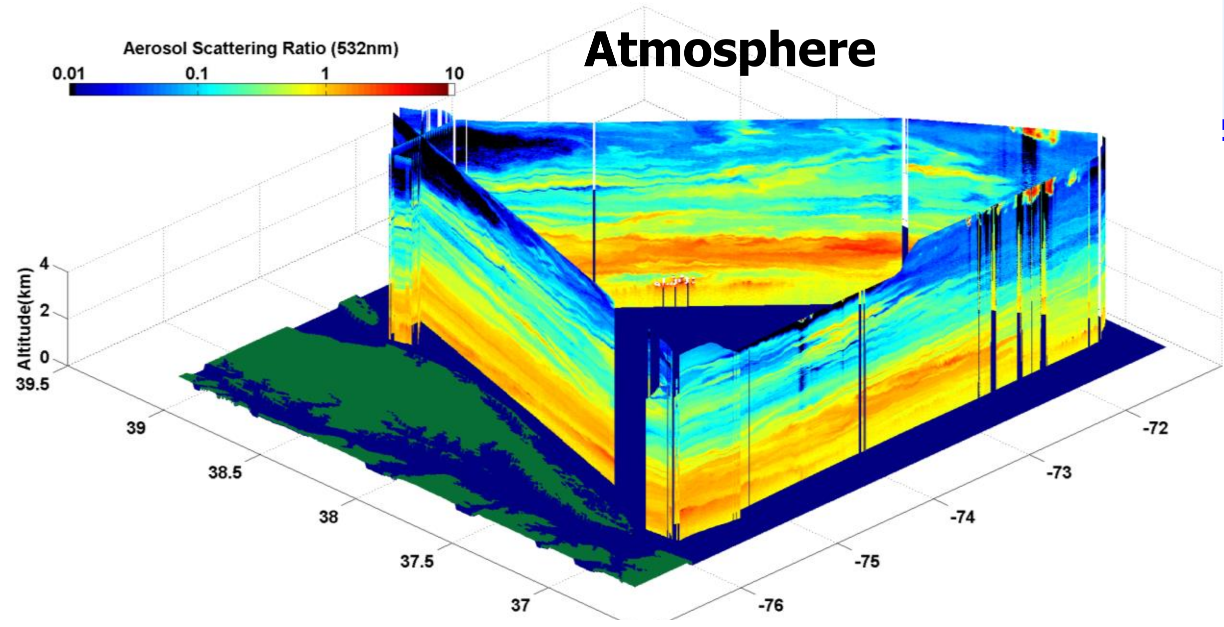
Date markers are casting locations for in situ profiling from the RRS James Cook

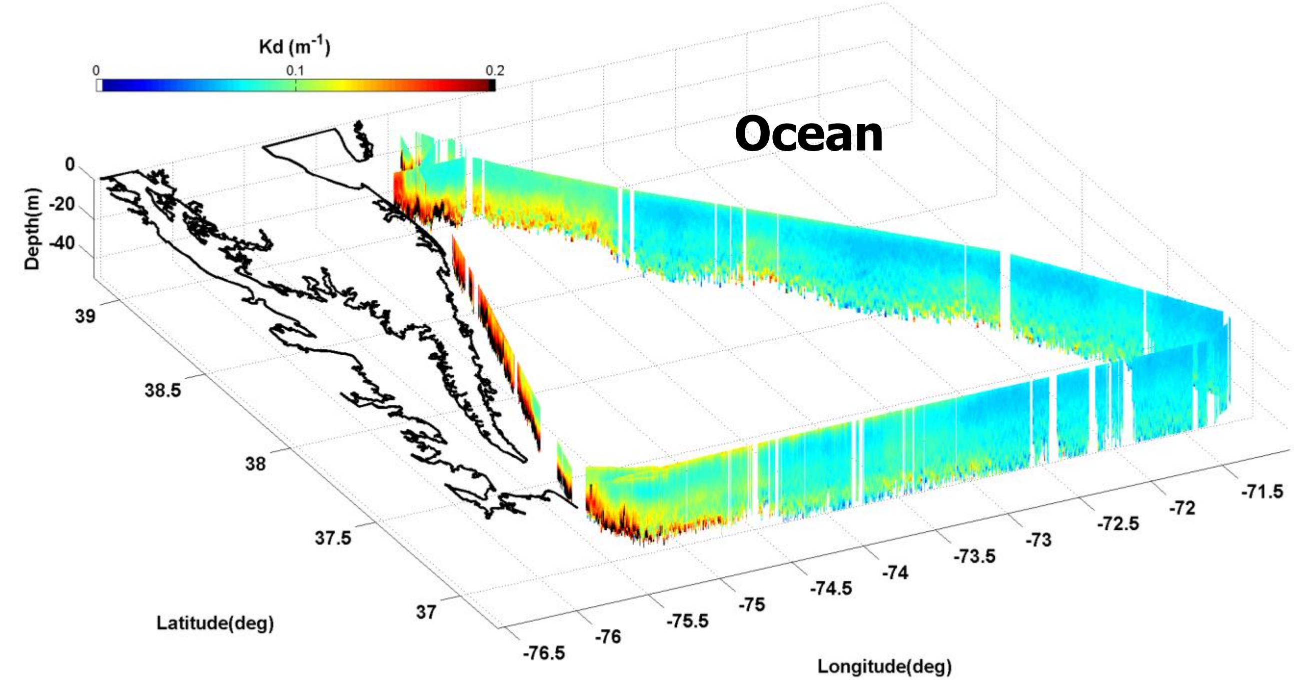
3-D Rendering of K_d profiles from one flight



- HSRL retrieval shows expected variations in diffuse attenuation from coastal to deep ocean

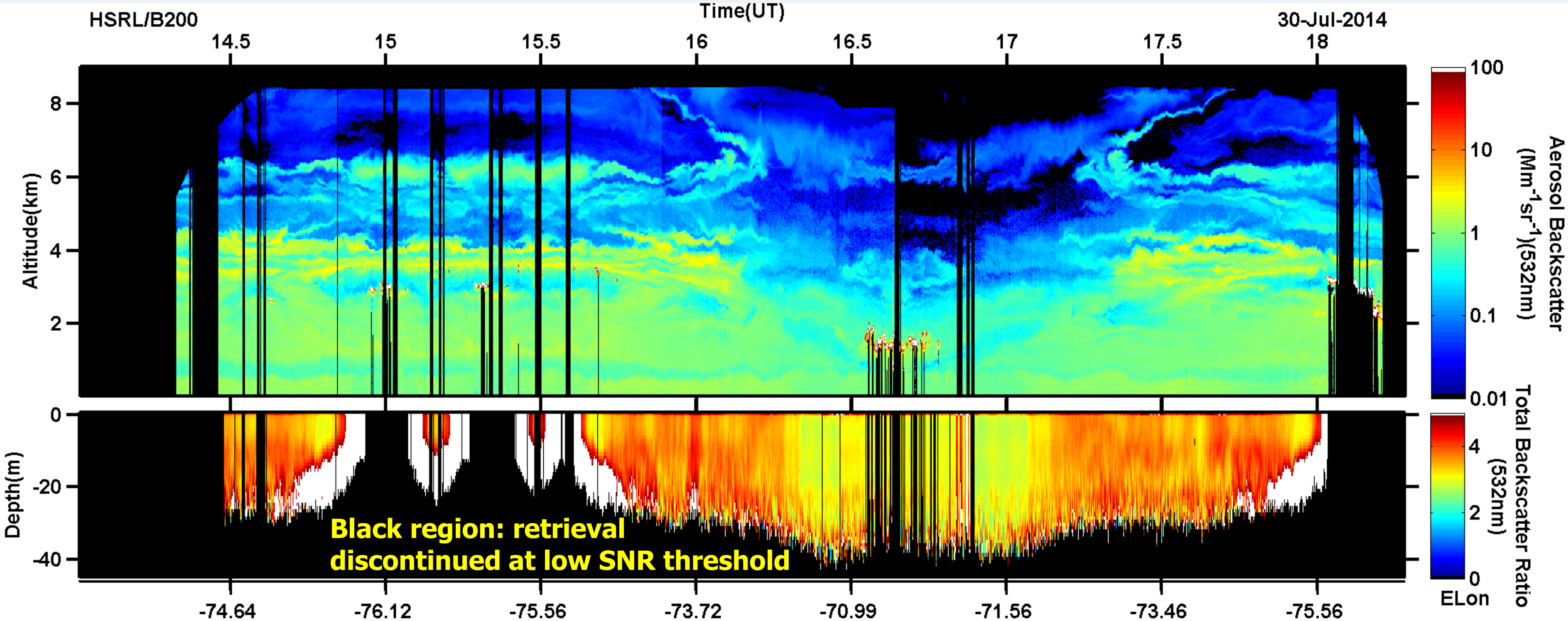
Coincident atmosphere-ocean products

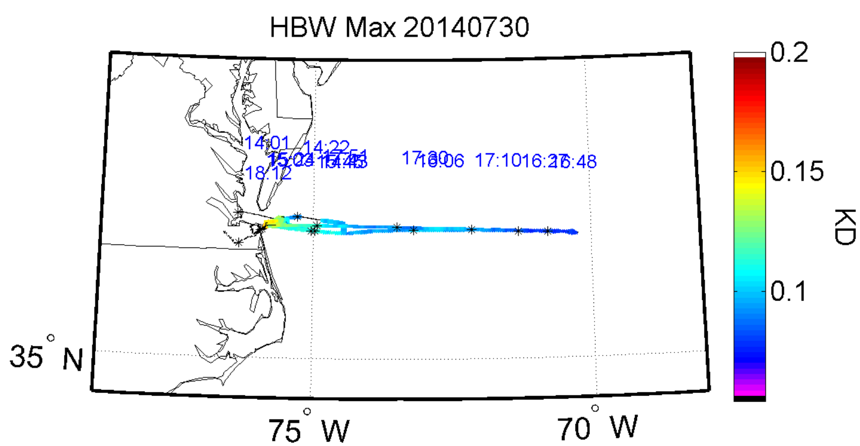




- Ocean-modified HSRL-1 and RSP polarimeter provide coincident atmospheric and ocean products
- Shown are lidar curtains for atmosphere and ocean on 31 July
- Significant aerosol loading on many of these flights could prove useful for understanding aerosol influences on passive ocean color retrievals

Unwrapped lidar curtain showing coincident atmospheric aerosol and ocean particulate backscatter

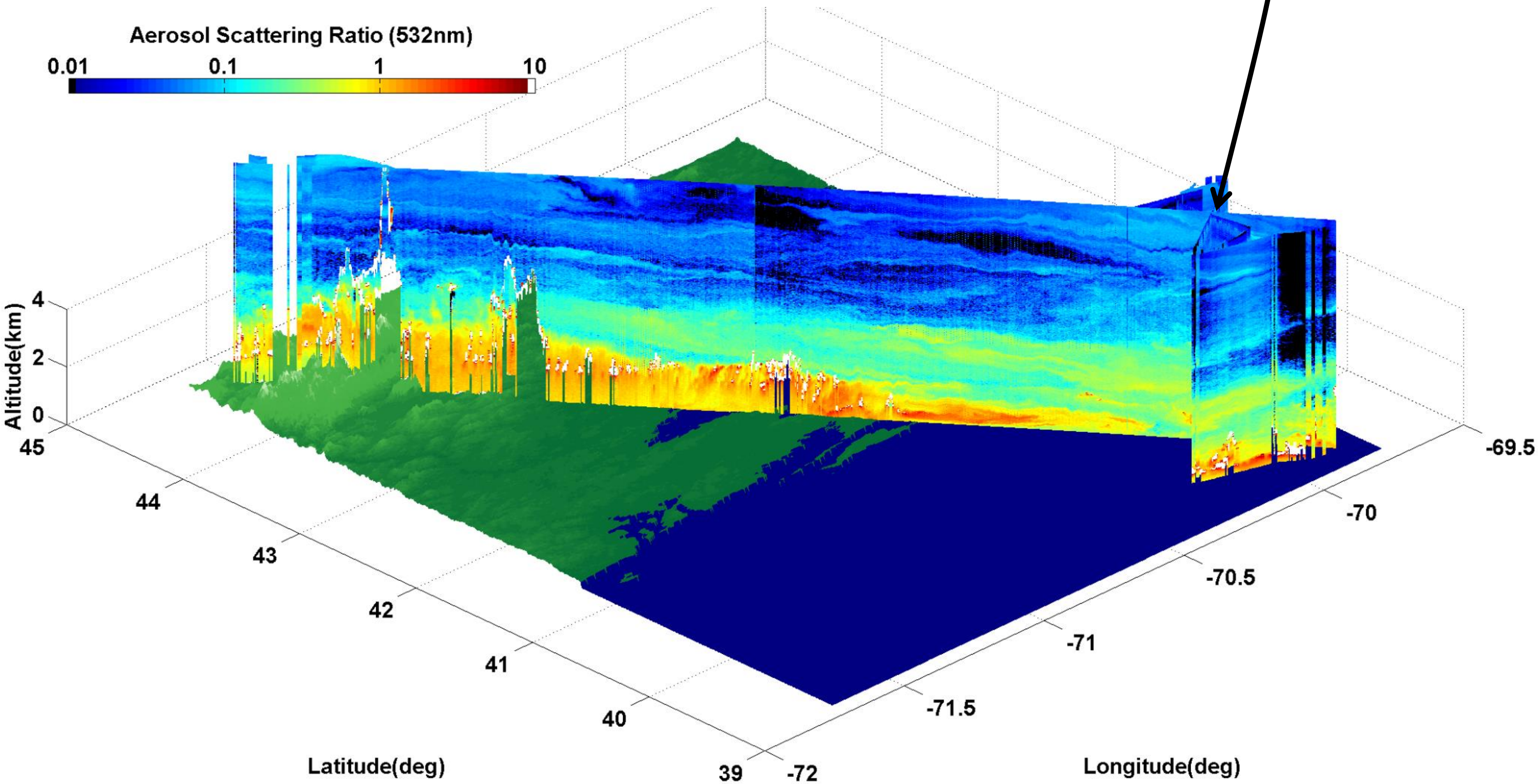




- Flight consisted of polarimeter patterns over Endeavor at mouth of Chesapeake Bay and survey east to deep water
- Data from Endeavor along entire track will improve conversions of lidar backscatter to hemispheric backscatter product (b_{bp}) used by ocean community

Trifecta: CALIPSO validation flight with coincidence of CALIPSO, aircraft, and ship

- Point of coincidence of Endeavor and UC-12 aircraft with CALIPSO
- Conducted polarimeter patterns over ship on same flight

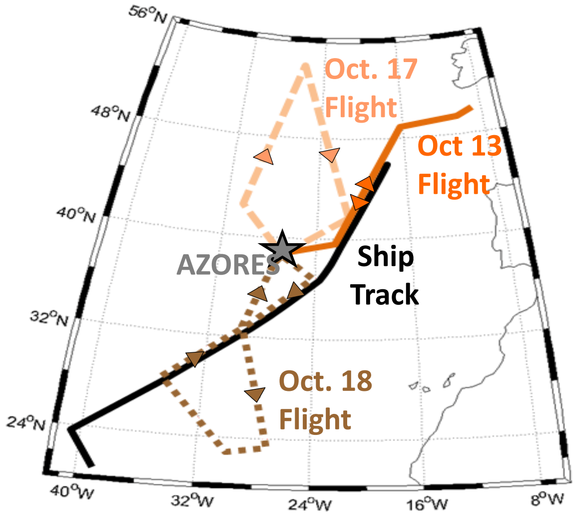


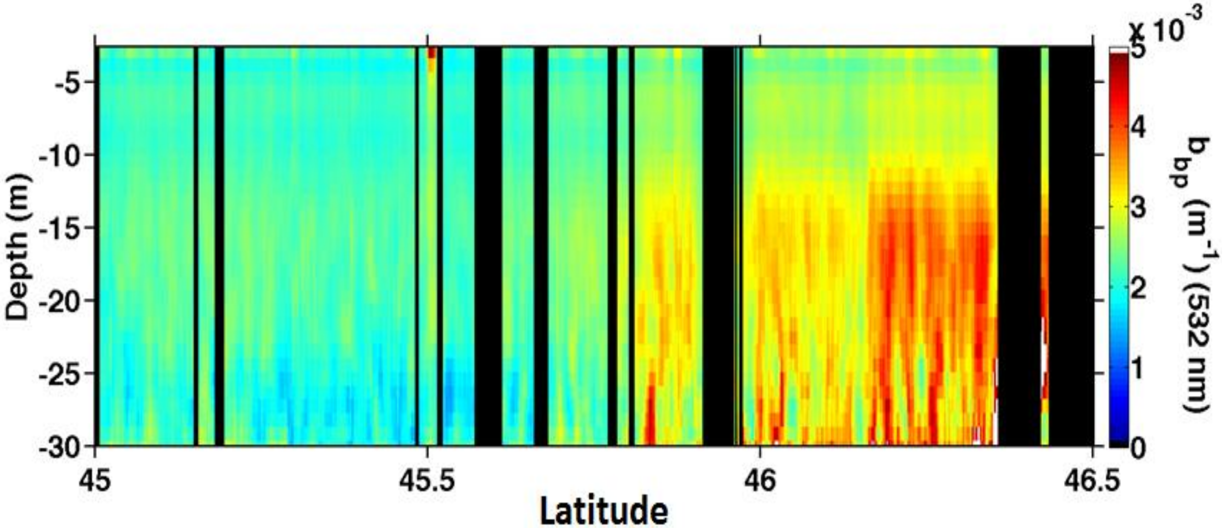
New Frontier in Ocean Remote Sensing

- The SABOR mission was the most extensive application to-date of the HSRL technique to ocean profiling
- HSRL technique is required to independently and accurately measure
  - Profiling of attenuation (K_d)
  - Profiling of particulate backscatter (b_{bp})
- Ocean profiling HSRL data from ACE promises to provide independent and more accurate estimates of Net Primary Productivity (NPP): the rate at which phytoplankton sequester CO_2 in the ocean. Ocean NPP is a large fraction of the global CO_2 budget and is currently highly uncertain due to a lack of information on the vertical profile of phytoplankton.
- Ship-based measurements from SABOR will enable team to validate and improve ocean lidar algorithms envisioned for ACE
- ACE, GOLD, IRAD, CALIPSO funding leveraged to enable
  - Optimization of lidar hardware (75% rebuild): install new SBIR laser, install new advanced detectors, develop new instrument controller and software, etc.
  - Execute more than 4 times the number of flights funded in by NASA SMD OBB

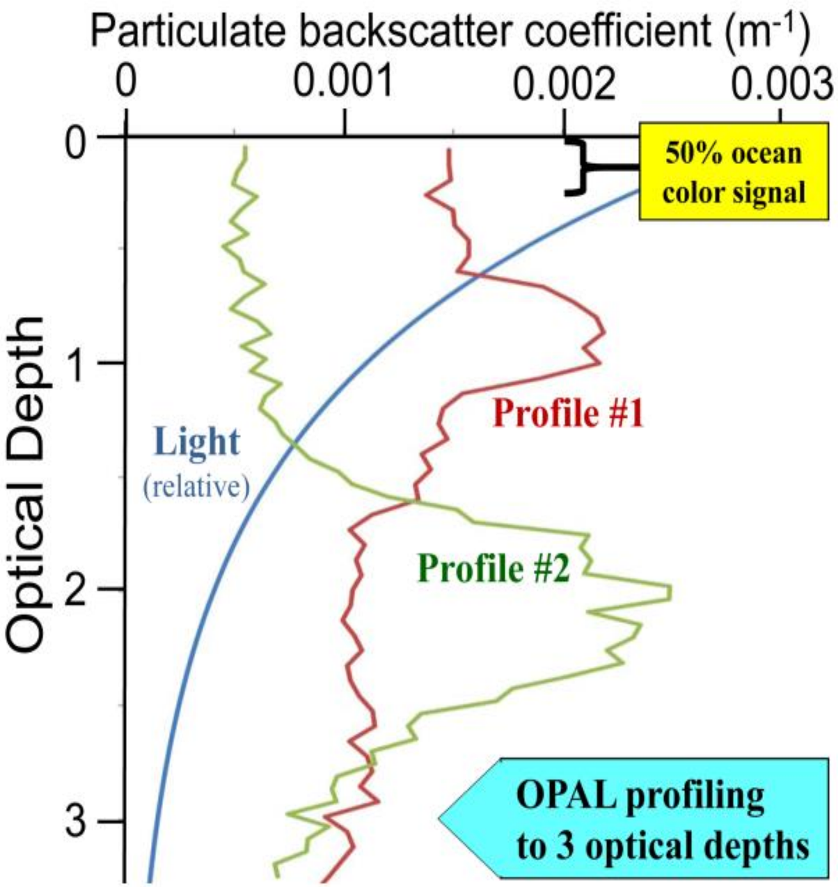
Ocean Profiling

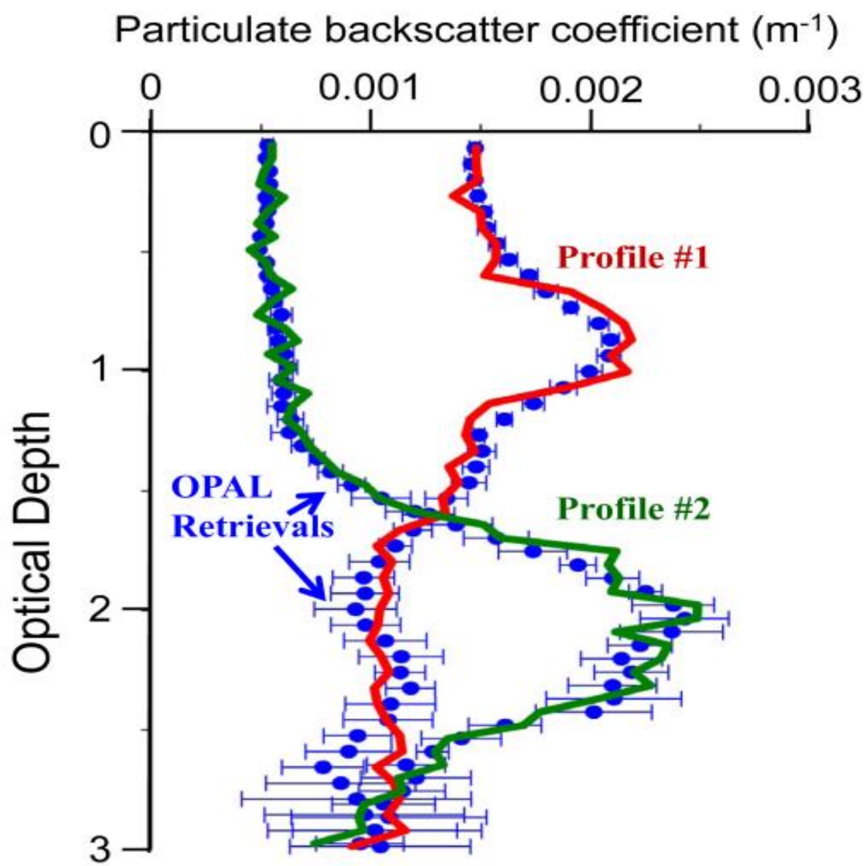
- Ocean profiling has been demonstrated with the airborne HSRL-1 instrument
- HSRL-1 was modified under the AITT program for high vertical resolution (1-m) ocean subsurface profiling at 532 nm
- First airborne mission conducted Oct 2012 on NASA P3-B





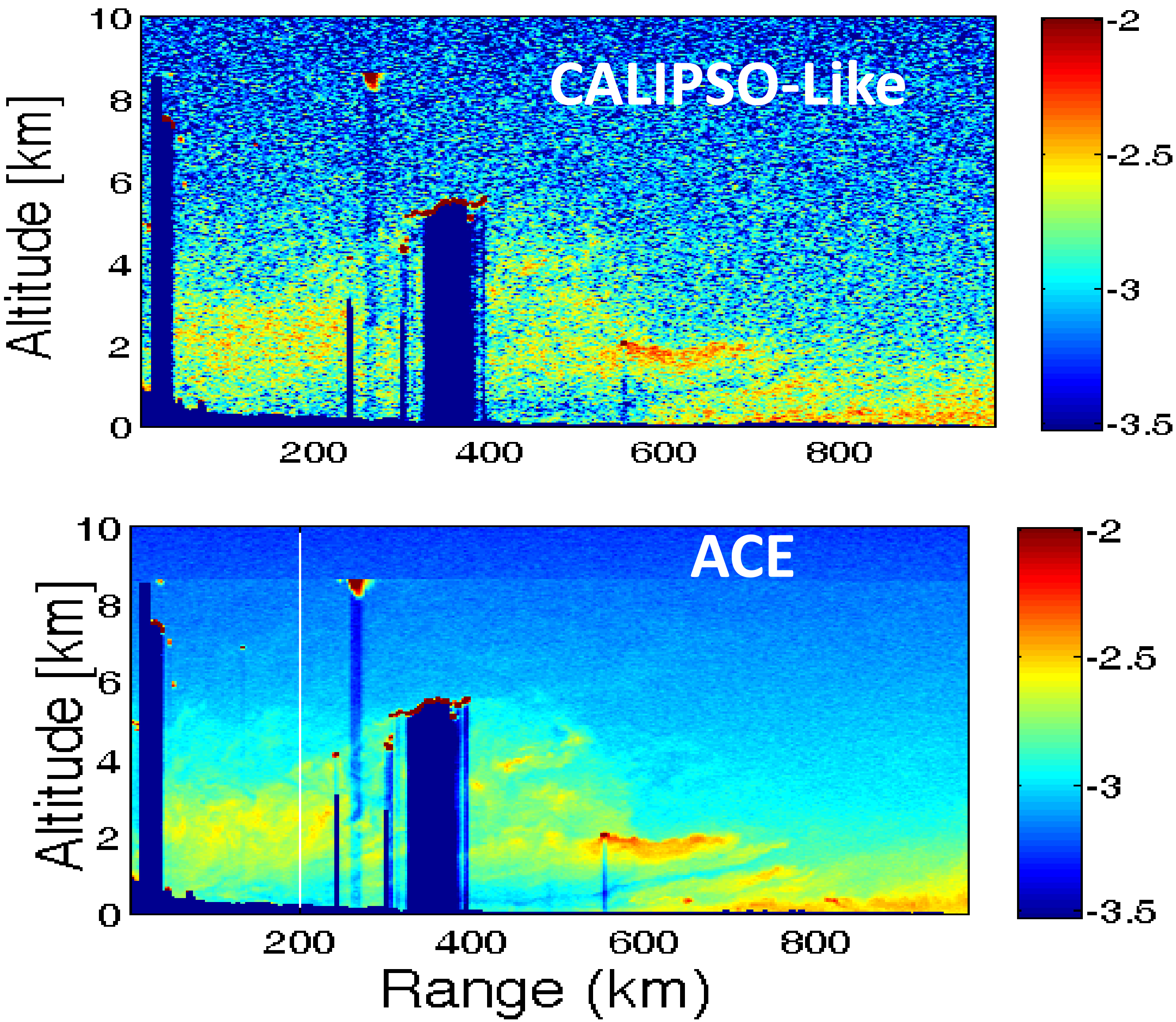
Simulation Retrievals from OPAL





- Measure vertical structure of phytoplankton to reduce uncertainties in NPP
- OPAL measurements will penetrate 70% of the euphotic zone (i.e., depth range where light levels are sufficient for photosynthesis).

Comparison with CALIPSO

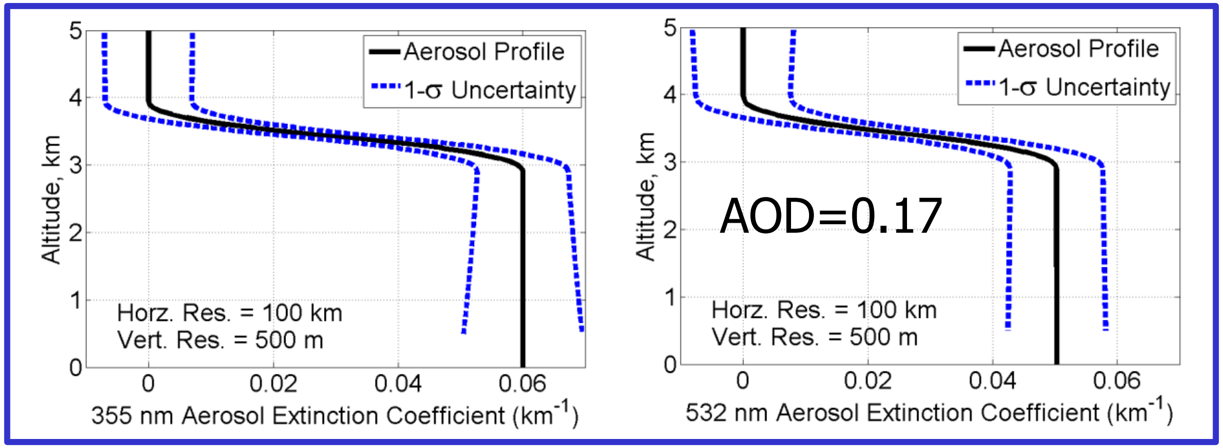


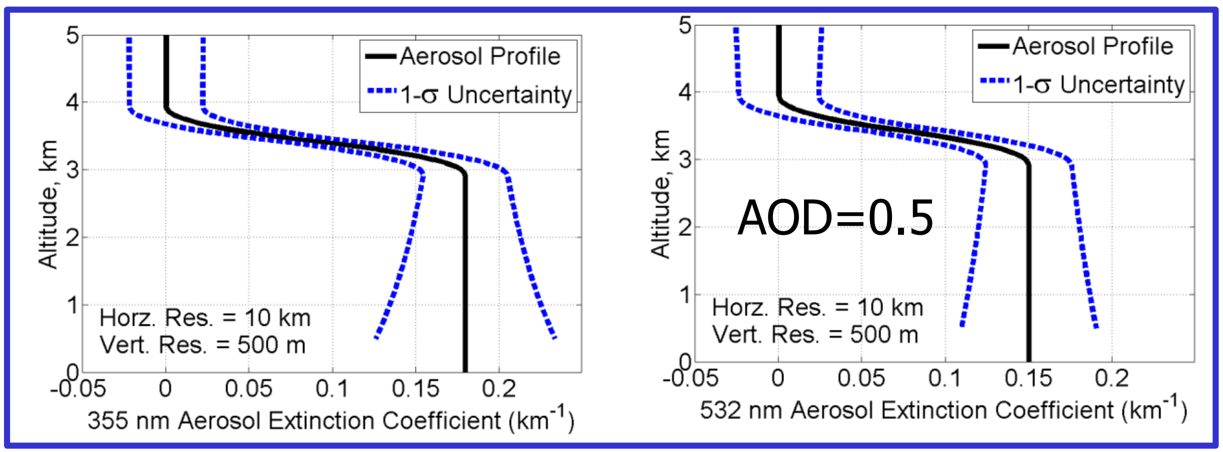
Simulated CALIPSO and ACE attenuated backscatter signal.

ACE achieves much higher SNR.

Input to simulator was an HSRL scene acquired at higher SNR.

Estimated random error in aerosol extinction

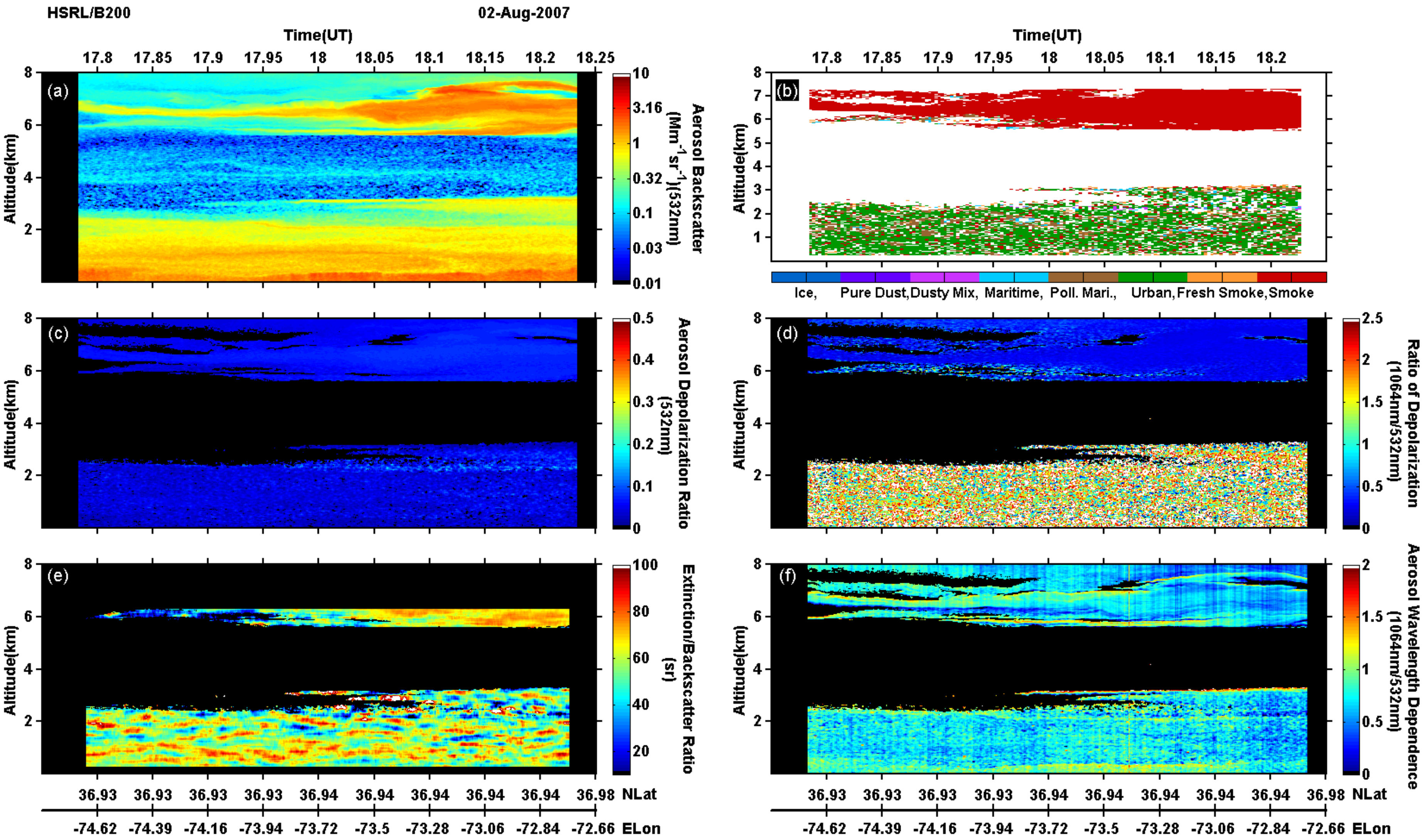




- Random error in extinction drives laser power, telescope size, etc.
- Shown are two daytime test cases identified in White Paper.
- 15% uncertainties achieved near top of layer in both cases
- More averaging required to achieve 15% threshold required as overlying optical depth increases.

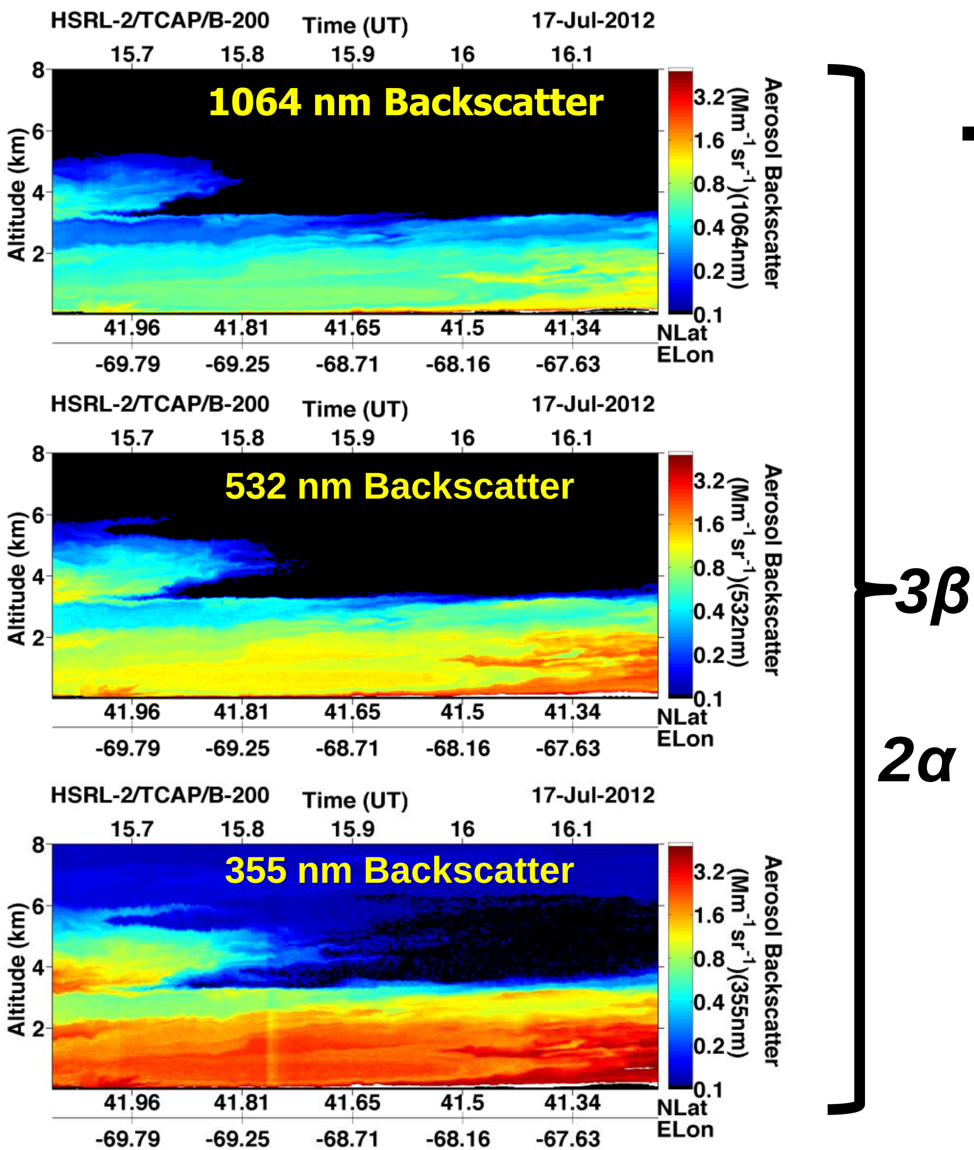
- Averaging resolutions and thresholds requirements were somewhat subjective and should be reviewed/refined.

Smoke over urban pollution



Airborne multi-wavelength "3β+2α" HSRL measurements from the TCAP field campaign

07/17/2012 TCAP flight on B200 aircraft



- High Spectral Resolution Lidar (HSRL) provides independent retrievals of aerosol extinction and backscatter
- HSRL-2 Capabilities
  - Backscatter at 355, 532, and 1064 nm
  - Extinction at 355 and 532 nm (HSRL)
  - Depolarization at 355, 532, 1064 nm